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U. S. ARMY HELICOPTER HYDRAULIC SERVOCYLINDER RELIABILITY AND MAINTAINABILITY INVESTIGATION

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Systems Associates, Incorporated

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By

James L. Huffman
Sheldon Dockswell

May 1973

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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SYSTEMS ASSOCIATES, INC.
LONG BEACH, CALIFORNIA

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This report was prepared by Systems Associates, Incorporated, under the terms of Contract DAAJ02-71-D-0003, Delivery Order 0001. It presents a discussion of the basic or underlying causes of reliability and maintainability (R&M) deficiencies that have been found to exist in servo-controlled hydraulic actuators (servocylinders) used on Army helicopters in the current inventory. Included in the report are discussions on the impact of design requirements, test requirements and procedures, quality assurance requirements and procedures, maintenance practices and procedures, training of maintenance personnel, and lagging technology upon various failure modes that are prevalent in hydraulic servocylinders. Also discussed is the influence of past Army procurement policies and procedures upon the basic causes of R&M deficiencies.

Results of this effort and other similar efforts have been used by this Directorate as a basis for initiating R&D programs to evaluate and recommend changes to design requirements, test requirements and procedures, and quality assurance provisions for hydraulic, electrical, flight control, and fuel systems and components.

The project engineer for this effort was Mr. Richard I. Adams, Military Operations Technology Division.

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U.S. ARMY HELICOPTER HYDRAULIC SERVOCYLINDER RELIABILITY AND MAINTAINABILITY INVESTIGATION

Final Report

Systems Associates, Inc. Report 73-009

By

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SUMMARY

This investigation was carried out to identify, isolate, and verify the causes of problems with servo controlled hydraulic actuators (hydraulic servocylinders) used on U.S. Army helicopters, and to trace the resulting effects on helicopter availability. Design requirements, quality assurance provisions, maintenance procedures and practices, test requirements, and procurement practices were analyzed to assess their impact upon the current problems.

The initial phase of the investigation was confined to the gathering of all pertinent failure data and documentation relating to hydraulic servocylinders. A Failure Modes and Effects Analysis (FMEA) was then performed upon the following three different hydraulic servocylinder designs:

1. UH-1H Collective Pitch and Cyclic Hydraulic Servocylinder

2. OH-6A One-Way Locking Actuator

3. CH-47 Stick-Boost Dual Actuating Cylinder

The FMEA identified foreseeable failure modes which are common to hydraulic servocylinders. All potential causes of the listed failure modes were then listed. These analyses revealed that a single type of servocylinder would be representative of the population of servocylinders. Therefore, the UH-1H collective/cyclic hydraulic servocylinder was used as a baseline upon which the data analyses were performed.

The analysis of the pertinent failure data and documentation revealed that five failure modes were responsible for over 90 percent of the total hydraulic servocylinder removals in a 6-1/2-year period. Subsequent analysis of the various policies, practices and procedures documents showed that they contain anomalies that contribute to the occurrence of the following predominant failure modes:

1. Leaking

2. Excessive Wear

3. Miscellaneous

4. False Diagnosis (no failure)

5. Unknown Reason

The lack of stringent basic and/or Army operational design requirements, lack of formalized quality assurance and testing plans and practices, and inadequate maintenance manuals were shown to be major contributing factors to the leaking failure mode. This mode accounts for approximately half of the servocylinder removals from U.S. Army helicopters. Removals of hydraulic servocylinders that were later found to have no detectable failure accounted for about one-third of all removals. This erroneous removal rate is directly attributed to inadequate training and ambiguities in maintenance documentation. The majority of the remaining removals were caused by normal wear for current state-of-the-art hydraulic servocylinders.

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INTRODUCTION

This investigation was performed to establish the basis of problems currently being experienced by the U.S. Army on current-inventory helicopter hydraulic servocylinders. This report describes the various activities that were performed with the primary intent of isolating the basic causes of existing failure modes. These activities covered data acquisition and analysis; failure modes and effects analysis; analysis of requirements, practices and procedures; recommendations for improvements in documentation and hardware; and cost savings that can be anticipated as a result of implementing the various recommendations.

Early in this investigation it became apparent that many similarities existed in the hydraulic servocylinder failure modes of various Army helicopters. Consequently, the UH-1H hydraulic servocylinder was used as the baseline design upon which this investigation was performed. This adoption of a baseline design does not in any way bias any recommendation stated. Therefore, all the revisions and solutions presented can be considered applicable to all current-inventory U.S. Army helicopters.

Hydraulic servocylinder data were gathered from the Reliability and Maintainability Management Improvement Techniques (RAMMIT) reports, the U.S. Army Aeronautical Depot Maintenance Center (ARADMAC) reports, the Navy Maintenance Material Management (3M) Data, and the Failure Rate Data (FARADA) Handbook for Helicopter Equipments. Data were also gathered from the 76th Aviation Group, Long Beach, California; the New Cumberland Army Depot; the 49th Aviation Battalion, Stockton, California; the Federal Aviation Administration, Long Beach, California; and the U.S. Army Agency for Aviation Safety, Fort Rucker, Alabama. These data were analyzed to determine hydraulic servocylinder failure modes and effects. Failure modes and effects analyses were performed on the following hydraulic servocylinders:

1. UH-1H Collective Pitch and Cyclic Hydraulic Servocylinder
2. OH-6A One-Way Locking Actuator
3. CH-47 Stick-Boost Dual Actuating Cylinder

Failure causes, determined from the Failure Modes and Effects Analysis (FMEA), were analyzed to determine their relationship to design requirements. Design requirements covered specification control documents and drawings, component selection criteria, military specifications and standards, design requirements to eliminate induced failures, and contract specifications. Quality assurance provisions included analysis of vendor manufacturer quality control and shipping inspections, airframe manufacturer receiving inspections, initial installation procedures, functional test procedures, mandatory inspection points, and component sampling procedures. Maintenance procedures and practices included investigation of maintenance manuals, periodic inspections, shelf-life considerations, failure criteria and detection, maintenance personnel skill level requirements, qualifications and training, special tool requirements and component accessibility. Test requirements and procedures were analyzed in terms of system compatibility testing requirements and procedures, qualification test requirements and procedures including environmental tests and procedures, flight test plans and porcedures, service test plans and procedures, and acceptance test procedures. Consideration was also given to how these test results should impact the production design of the servocylinders.

A cost model was developed to predict costs incurred by hydraulic servocylinder failures as a function of unit cost, installation time, labor costs, mean time between failures, and fleet size. Existing and proposed hydraulic servocylinders were compared using the model to determine costs. Revisions and solutions were made for changes in documentation and hardware in each of the areas within the Requirements, Procedures, and Practices section.

FAILURE DATA ANALYSIS

Hydraulic servocylinder failure data were compiled, categorized, and analyzed for the CH-47, UH-1H, and AH-1G helicopters to determine which failure modes produce the majority of unscheduled removals. This analysis was limited to these three types of helicopters equipped with hydraulic servocylinders. Additionally, these three types of helicopters represent the bulk of the U.S. Army's current-inventory helicopters. The investigation was designed to produce an ordered set of candidates for improvement recommendations. The order of the set concentrates on those candidates that offer the greatest potential increase in Mean Time Between Failures (MTBF) for the lowest expenditure of available resources of money and manpower.

RELIABILITY AND MAINTAINABILITY MANAGEMENT IMPROVEMENT TECHNIQUES (RAMMIT) ANALYSIS

The UH-1H, AH-1G, and CH-47 RAMMIT reports were used as a basis for identifying and reducing failure data. The two types of RAMMIT reports used in this analysis are as follows:

1. Aircraft Component Time Since Installation, Overhaul or New (ACTION) Reports

2. Major Item Special Study (MISS) Reports

Aircraft Component Time Since Installation Overhaul or New Analysis

Three ACTION reports (UH-1H, AH-1G, and CH-47) were analyzed during this investigation. The period covered by each ACTION report ranged from 1 January 1964 through 30 June 1971. The type of data in the ACTION report structure provided a rationale for removal in terms of Failure Mode (FM) and of Flight Hours Since Last Installation (TSLI), Since Overhaul (TSLO), and Since New (TSN), for each part number over a 6-1/2-year period. Table I summarizes the failure mode data for the UH-1H, AH-1G, and CH-47 helicopters.

In order to use the RAMMIT data most efficiently, the following procedure was followed:

1. Determine which failure modes comprised the majority of removals.

2. Determine occurrences (number of removals) affected by failure modes selected in step 1.

TABLE I. RAMMIT DATA SUMMARY						
	Helicopter Model Number					
	CH-47A		AH-1G		UH-1H	
Failure Mode	Percent of Total Failures	Cumulative Percent	Percent of Total Failures	Cumulative Percent	Percent of Total Failures	Cumulative Percent
Leaking	42	42	47	47	46	46
No Failure	33	75	20	67	33	79
Unknown Reason	10	85	8	75	6	85
Internal Failure	7	92	6	81	2	87
Excessive Wear	3	95	4	85	4	91
Other	5	100	15	100	9	100
Total Number of Removals	5298		1688		2056	

3. Use these data to point to causes of any or all failure modes.

As indicated in Table I, the primary failure modes are as follows:

1. The Leaking Servocylinder Failure mode accounts for the greatest single cause for removals. This indicates repeated malfunctioning of the various actuator seals. The potential causes for these leaking seals are developed in the Requirements, Procedures and Practices portion of this report.

2. The No Failure mode includes those servocylinder removals caused by scheduled maintenance and false diagnosis. In all of these removals it is assumed that the servocylinder was otherwise serviceable, and could have been reinstalled or returned to inventory for subsequent use.

3. The Unknown Reason mode accounts for known removals for which a failure cause was not assigned.

4. The Internal Failure and Excessive Wear modes account for approximately 10 percent of all servocylinder removals. Analysis shows that these removals occurred at about 300 flight hours since new. This indicates a loading and/or environmental application problem.

5. The Other Failure mode accounts for the remaining servocylinder removals. These other failure modes comprise a relatively small percentage of total removals (less than 10 percent).

Major Item Special Study Analysis

Two MISS reports were analyzed during this study. These reports treated the hydraulic servocylinder used on UH-1H and AH-1 helicopters. The period covered in each MISS ranged from 1 January 1964 through 30 June 1970.

The MISS results correlate well with the ACTION report data analyzed during this investigation. The types of hydraulic servocylinders with the highest failure rate in each MISS were among those types identified during the ACTION report analysis as producing over 50 percent of the recorded failures.

Investigation of failure mode analysis of additional aircraft was considered to be unnecessary because a definite failure mode pattern was established by the CH-47, AH-1G and the UH-1H helicopter data. The UH-1 series is therefore considered as a representative baseline because it exists in the greatest numbers in the Army inventory, and provides the greatest quantity of relevant data.

FEDERAL AVIATION ADMINISTRATION REGIONAL MALFUNCTION OR DEFICIENCY "TREND LIST" ANALYSES

The Federal Aviation Administration (FAA) Regional Malfunction or Deficiency (M or D) "Trend List" was also examined for servocylinder failure data on general aviation helicopters. Table II displays a matrix of these nonmilitary servocylinder failure data. In addition, Airworthiness Directives (AD's) were obtained from the FAA. An examination of these AD's did not produce data applicable to the present study.

The FAA data as shown in Table II does not account for nonfailure removals, in contrast to the RAMMIT data. However, the "leaking" failure mode, percentage-wise, corresponds reasonably with the

TABLE II. FAA REGIONAL M OR D "TREND LIST"

Hydraulic Servocylinder Failure Mode	General Aviation Helicopters Percent of Total Failures	Cumulative Percent of Failures
Leaking	36	36
Excessive Wear	46	82
Broken	18	100
Total Number of Removals	22	-

servocylinder removal causes in the military environment. Analysis of time since installation of servocylinders in general aviation helicopters reveals a higher flight-hour utilization. This can be attributed to a less severe operating envelope and environment, and possibly to more competent maintenance personnel.

NAVY 3M ANALYSIS

Navy 3M data from the Maintenance Support Office at Mechanicsburg, Pennsylvania, were also examined. The format used did not include material failure causes for subsystem components. Reports which track failure modes for certain chosen end items are generated locally at the user organizations. For instance, at the Marine Corps Air Facility, Santa Ana, California, such data were being generated. However, the data did not contain suitable information for the present analysis. Their emphasis was placed upon avionics systems failures.

FAILURE MODES AND EFFECTS ANALYSIS

A Failure Modes and Effects Analysis (FMEA) was performed early in the program to identify the potential failure modes associated with hydraulic servocylinders, their causes, and their effects upon the operational performance of various helicopters. This analysis formed a basis for later detailed analyses of the underlying causes for the premature failures of the hydraulic servocylinder. The FMEA also established the basis for the suggested remedy or solution for future design and procurement specifications, maintenance practices and procedures, and inspections and maintenance verification checks. These theoretical remedies were then verified or discarded during the remainder of this investigation.

METHOD OF ANALYSIS

The FMEA provides potential failure mode and effect identifications for the most prevalent hydraulic servocylinder types used in current-inventory U.S. Army helicopters. An FMEA was performed for each pertinent element of representative hydraulic servocylinders.

The columnar headings of the FMEA data sheets are defined as follows:

1. Item/Function: Identifies a discrete hydraulic servocylinder type and its function in the helicopter.
2. Failure Mode: Defines the potential failure modes associated with the functioning of the hydraulic servocylinder identified.
3. Probable Failure Cause: Identifies the probable causes of the failure modes. The relevance of these causes is apt to change during different phases of operations, so consideration was given to the dynamics of the operation, rather than the likelihood of occurrence.
4. Failure Effect—Subassembly: Identifies the effect of the potential failure on the performance of the hydraulic servocylinder assembly by itself without consideration of the other related components or functions of the subsystem.
5. Failure Effect—Next Assembly: Identifies the effect of the failure in combination with other components or functions to determine if there is either a compounding or mitigating effect on the actuated subsystem.

6. Failure Effect—End Item: Identifies the failure effect in combination with other subsystems or functions to determine if there is either a compounding or a mitigating effect on the helicopter and/or flight crew.

7. Design/Maintenance Compensating Provisions: Defines the manner in which the existing design features compensate for the failure mode and/or reduce the probability of occurrence. The maintenance provision available to reduce the probability of occurrence is based upon the assumption that preventive maintenance schedules are strictly adhered to as provided in the applicable Technical Manual (TM).

8. Remarks/Recommendations: Presents remarks pertinent to the usage and recommendations involving interface with other systems. Presents recommended corrective actions whenever possible.

The following procedure is used on the FMEA forms in order to eliminate needless repetition of phrases in the "Design/Maintenance Compensating Provisions" and "Remarks/Recommendations" columns:

1. Each "Probable Failure Cause" associated with a distinct "Failure Mode" is assigned a number.

2. Then the Design/Maintenance Compensating Provisions and/or Remarks/Recommendations are presented as they minimize or eliminate each particular numbered Probable Failure Cause (or group of causes) that contributes to the specific Failure Mode being addressed.

FAILURE ANALYSES

Failure analyses of 3 representative hydraulic servocylinders were performed to identify typical causes of failure modes and their effects. The 3 hydraulic servocylinders and their functional purposes selected for the analyses are as follows:

1. UH-1H Collective Pitch and Cyclic Hydraulic Servocylinder— The collective pitch hydraulic servocylinder reduces operational loads on the collective pitch control system and facilitates pilot control of the helicopter. The cyclic control hydraulic servocylinders reduce the effort required for control and reduce feedback of forces from the main rotor. One irreversible valve is attached to each servocylinder for both collective and cyclic control systems. The irreversible valve permits hydraulic fluid to flow only toward the servocylinder. The valve prevents flight-induced loads (feedback

forces) from being transmitted back to the pilot's control stick. The irreversible valve also provides the pilot with safe control of the helicopter in the event of a hydraulic system failure.

2. OH-6 One-Way Locking Actuators—The cyclic control system one-way lock (Uniloc) is essentially a self-contained closed-loop hydraulic unit. An intergal check valve prevents unwanted aft movement of the cyclic stick and shunts the feedback force into the airframe structure.

3. CH-47 Stick-Boost Dual Acting Cylinder — Four stick-boost actuating cylinders are used in the flight control system. These four cylinders transmit the control forces from the cockpit controls to the forward upper and aft flight controls. The four cylinder controls are for pitch, roll, yaw, and thrust.

These 3 selected designs display the majority of the current design concepts for hydraulic servocylinders and lend themselves to illustrate the intent of this technical report. Consequently, the FMEA's were limited to these 3 types of hydraulic servocylinders.

In general, the hydraulic servocylinder amplifies the pilot's control stick forces to the rotor. It also dampens sudden and/or excessive forces from being applied to the pilot and/or copilot by the rotor (i. e., feedback).

The irreversible valve is included in the UH-1H servocylinder FMEA for completeness and to facilitate comprehension of the cause-and-effect relationships that are relevant to the UH-1H situation.

Figure 1 is an exploded view of the UH-1H collective/cyclic hydraulic servocylinder. The physical and functional interrelationships between all the parts shown make them inseparable when failure modes and the effects of either are considered in any detail. The FMEA for this servocylinder is shown in Figure 2. The Uniloc for the OH-6 is shown in Figure 3 and its FMEA in Figure 4. Figures 5 and 6 show the CH-47 actuating cylinder and its FMEA (respectively).

The primary failure mode of all these servocylinders was external leakage. The largest contributing factors for this failure mode were:

1. Worn barrel surfaces (except CH-47).

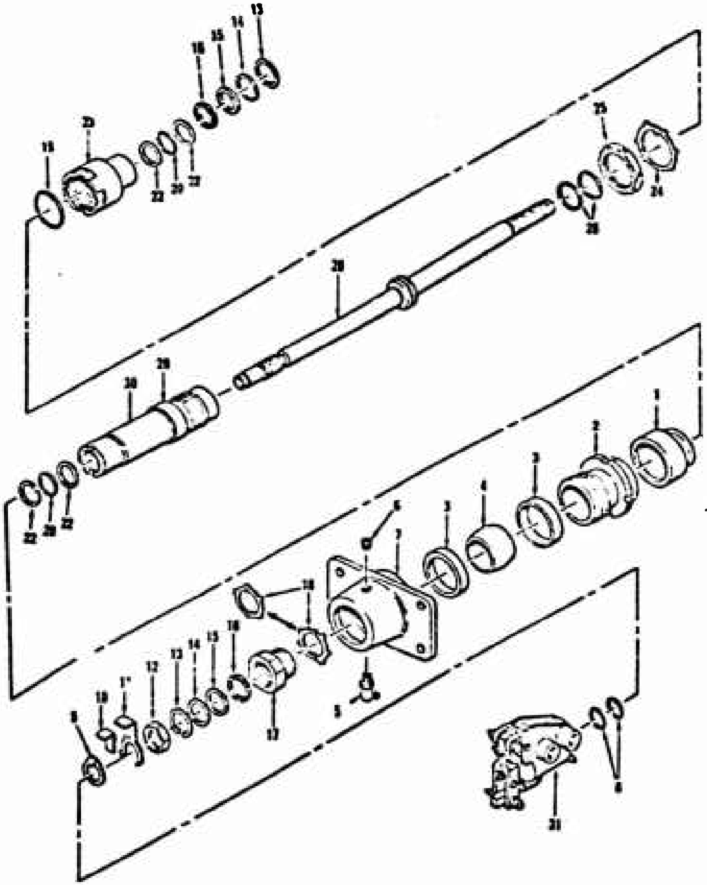
2. Worn and deteriorated seals, scrapers and tetrafluorethylene (TFE) cap sleeves.

3. Side loading induced by transverse vibration into the servocylinder.

4. Inadequate design constraints placed upon the design, whereby the requirements of the Army's operational environment exceed the inherent design of the servocylinder.

The results of the FMEA and failure data analyses display a predominant and parallel theme: leaking is the most prevalent failure mode, and its probable causes are the same for the servocylinders investigated. The CH-47 actuating cylinders steel barrel design, versus the generally accepted practice of using aluminum alloys, eliminated the leaking failure mode.

Therefore, in the interest of comprehension, the UH-1H hydraulic servocylinders will be used in the remainder of this report to represent all U.S. Army helicopter hydraulic servocylinders.



1.	BOOT	11.	LOCKING KEY	21.	TFE BACKUP RINGS
2.	NUT	12.	NUT	22.	CAP
3.	BUSHING	13.	RING	23.	LOCK KEY
4.	BEARING	14.	RETAINER	24.	NUT
5.	FITTING	15.	SCRAPER	25.	SEAL
6.	PLUG	16.	WASHER	26.	PISTON ROD
7.	HOUSING	17.	RETAINER	27.	PLATE
8.	PACKING	18.	WASHER	28.	CYLINDER ASSEMBLY
9.	WASHER	19.	PACKING	29.	SERVO HEAD ASSEMBLY
10.	KEY	20.	PACKING		

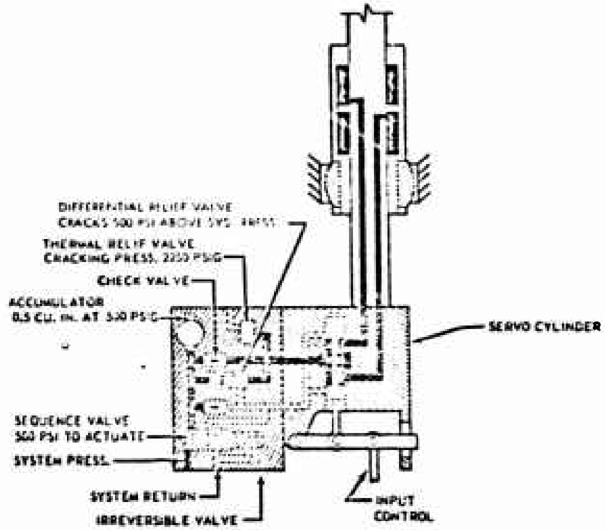


Figure 1. UH-1H Collective/Cyclic Hydraulic Servocylinder (Exploded View).

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13. ABSTRACT

This investigation was carried out to identify, isolate, and verify the causes of problems with hydraulic servocylinder actuators used on U.S. Army helicopters, and to trace the resulting effects on helicopter availability. Design requirements, quality assurance provisions, maintenance procedures and practices were analyzed to assess their impact upon the current problems.

The analysis of the pertinent failure data and documentation revealed that 5 failure modes were responsible for over 90 percent of the total hydraulic servocylinder removals in a 6-1/2-year period. Subsequent analysis of the various policies, practices and procedures showed that these documents contain anomalies that contribute to the occurrence of the 5 predominant failure modes. The lack of stringent basic design requirements, quality control, and adequate maintenance manuals was shown to be a major contributor to the leaking failure mode. This mode accounts for approximately half of the servocylinder removals from U.S. Army helicopters.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Conformity						
Cyclic rate						
Dust						
Extrusion						
Filtration						
Leaking						
Maintenance requirements						
Qualification						
Seal, nonsliding						
Seal, "T"						
Specification development						
Test requirements						
Vibration						

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
COLLECTIVE PITCH AND CYCLIC HYDRAULIC SERVOCYLINDER The collective pitch and cyclic hydraulic servo-cylinder: o Reduces operational loads on the flight control system. o Facilitates pilot control of the helicopter. o Reduces feedback forces from the main rotor. Each hydraulic servo-cylinder has an irreversible valve attached, which: o Permits hydraulic fluid to flow only toward the servocylinder. o Prevents flight-induced loads (feed-back forces) from being transmitted back to the pilot's control stick. o Provides the pilot with safe control of the helicopter in the event of a hydraulic system failure. Each part is referenced parenthetically by number to Figure 1.	Leaks hydraulic fluid externally.	1) Worn rod end scraper (15). 2) Worn packing/seals (20). 3) Piston rod (28) surfaces worn 4) TFE cap sleeves (22) worn. 5) Improper Filtration: o Improper filter installed. o Infrequent replacement of filter element. o Contaminated hydraulic fluid clogs filter. 6) Packings/seals (20) damaged during refurbishment.	Ingestion of contaminates will cause excessive wear of: o Packings/seals (20). o TFE cap sleeves (22). o Piston rod (28) surfaces. o Barrel (30) surfaces. o Rod end scrapers (15).	Leaking hydraulic servo-cylinder may cause response to the pilot's commands to be slow.	Leaking hydraulic servocylinder may cause degradation of helicopter flight performance		5) The hydraulic system contains provisions for a 15 micron filter to reduce the amount of contaminants in the hydraulic system. The daily preventive maintenance check, TM 55-1520-210 PMD, Sequence 4.7 requires that the hydraulic filter be checked for appearance of red indicator button. This red button indicates that the filter is clogged and the system is being contaminated. The periodic (100 hour) preventive maintenance check, TM 55-1520-210 PMP, Sequence 4.8 requires that an oil sample be taken from bottom of hydraulic system reservoir; if contaminant is evident, flush system and reservoir. Sequence 4.8A requires that the paper filter elements be renlaced during each 100 hour periodic check. Sequence 4.8B requires that the metal filter element be replaced during every tenth 100 hour periodic check.	1) The rod end scraper design requirement should be improved to eliminate the ingestion of contaminant which induce excessive wear of the rod end scrapers. 2) The present packing design requirement should be improved to use the "T" seal design concept. This design concept is described in detail in the Solutions section of this report. 3) The present TFE cap sleeve design should be improved to use a graphite or rouge-filled TFE cap sleeve in lieu of the present glass-filled TFE to reduce wear of the moving surface. This concept is described in detail in the Solutions section of this report. An alternative concept may be the use of the "T" seal with its split backup ring in lieu of the present "O" ring with the TFE cap sleeve. This concept is described in detail in the Solutions section of this report.

Figure 2. UH-1H Collective Pitch and Cyclic Hydraulic Servocylinder FMEA.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							(The following are applicable to probable failure causes No. 1, 2, 3, and 4 only.) The daily preventive maintenance check, TM 55-1520-210 PMD, Sequence 3.4 requires that the servocylinder be inspected for security, damage and evidence of leaks. The daily preventive maintenance check TM 55-1520-210 PMD, Sequence 4.7 requires that the exposed hydraulic pistons be wiped clean.	4) The present packing seal with cap sleeve design concept should be improved to use the "T" seal design concept. This design concept is described in detail in the Solutions section of this report. 5) When 15 micron filtration is required, the specifications and maintenance manuals should state that this is a 15 micron absolute filter. A nominal 15 micron filter will allow a mean filtration of 23 microns and an absolute of 30 microns. The result of the use of a nominal 15 micron filter is damage to other hydraulic system components. The daily preventive maintenance check, TM 55-1520-210 PMD, Sequence 4.7 should also require the replacement of the filter and a flushing of the system whenever the red indicator button is observed.

Figure 2 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								6) The inherent design of "O" ring seals with the TFE cap sleeve leads to difficulty in installing these "O" rings. Consideration should be given to use packing seal design such as the "T" seal concept. The "T" seal design, which uses split backup rings made from flexible material, provides for quick and easy installation without the inherent installation damage of current design "O" rings with the TFE cap sleeve. This design concept is described in detail in the Solutions section of this report. A) (Applicable to probable failure causes No. 1, 2, 3, and 4 only.) The daily preventive maintenance check should include a requirement to cycle the flight control under pressure and observe for leaks.

Figure 2 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								B) (Applicable to probable failure causes No. 1, 2, 3, 5 and 6.) Replace present sliding seal hydraulic servocylinder with an improved servocylinder incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.
	Leaks hydraulic fluid internally.	1) Worn packings seals (19). 2) Barrel (30) surfaces worn.	Servocylinder may tend to operate excessively which will result in increased wear of o Packings seals (20). o Rod end scrapers (15). o TFE cap sleeves (22). o Piston rod (28) surfaces. o Barrel (30) surfaces.	Leaking hydraulic servocylinder may cause response to the pilot's commands to be slow.	Leaking hydraulic servocylinder may cause degradation of helicopter's flight performance.		None.	(Applicable to both probable failure causes.) The periodic (100 hour) preventive maintenance check should include a requirement to operationally check the servocylinders to ensure that they do not creep due to the internal leakage. Replace present sliding seal hydraulic servocylinders with an improved servocylinder incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.

Figure 2 - Continued.

<table>
<tr><th rowspan="2">ITEM/FUNCTION</th><th rowspan="2">FAILURE MODE</th><th rowspan="2">PROBABLE FAILURE CAUSE</th><th colspan="3">FAILURE EFFECT</th><th rowspan="2"></th><th rowspan="2">DESIGN/MAINTENANCE COMPENSATING PROVISIONS</th><th rowspan="2">REMARKS RECOMMENDATIONS</th></tr>
<tr><th>SUBASSEMBLY</th><th>NEXT ASSEMBLY</th><th>END ITEM</th></tr>
<tr><td></td><td>Servocylinder binds.</td><td>Side loading due to transverse vibration.</td><td>Side loading of servocylinder causes.
o Piston rod (28) to bend.
o Piston rod to wear excessively due to excessive friction in:
o Packings seals (20).
o Rod end scrapers (15).
o End cap (23).
o TFE cap sleeves (22).</td><td>Side loading of servocylinder causes excessive friction in the flight control system.</td><td>Excessive friction may cause degradation of helicopter's flight performance.</td><td></td><td>The daily preventive maintenance check, TM 55-1520-210 PMD, Sequence 3.4 requires that the servocylinder be inspected for security, damage and evidence of leaks.
The daily preventive maintenance check, TM 55-1520-210 PMD, Sequence 4.7 requires that the exposed hydraulic pistons be wiped clean.</td><td>The periodic (100 hour) preventive maintenance check should include a requirement to operationally check the flight control system using a spring tension meter to measure system friction.
The present design concept of the Uni-ball Assembly (2, 3, 4, and 7) should be improved to use a large one-piece bearing. This design concept eliminates the inherent galling and binding of the Uni-ball and is described in detail in the Solutions section of this report.
Replace present sliding seal hydraulic servocylinder with an improved servocylinder incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.</td></tr>
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</table>

Figure 2 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
	Collective stick will not stay in position or servo-cylinder oscillates excessively.	Springs on collective servocylinder are: o Improperly adjusted. o Binding. o Fatigued.	Possible damage to spring. Excessive oscillation of servo-cylinder will accelerate the wear of o Piston rod (28) surfaces. o Barrel (30) surfaces. o Rod end scrapers (15). o Packings seals (19, 20). o TFE cap sleeves (22).	Excessive oscillation of the servocylinder will accelerate the wear of other flight control components, i.e., rod end bearings.	Excessive oscillation of the servocylinder may cause o Degradation of helicopter's flight performance. o Pilot fatigue.		The collective power lever spring tension is adjustable.	A pull scale attached to the collective stick should show from 8 to 10 pounds constant force. After the hydraulic power is on, the collective stick should be in full down position and the pilot's friction adjustment nut should be full off. This check should be performed daily.
	Servocylinder chatters.	1) Air in servo-cylinder. 2) Servocylinder mounting Uni-ball Assembly (2, 3, 4, 7) is o Worn. o Loose (un-loading of Uni-ball Assembly.	Possible damage to packings seals (19, 20) caused by surging hydraulic pressure.	Chattering of servo-cylinder may cause excessive point loading of flight control rods and bearings with resulting fatigue and wear	Chattering of servo-cylinder may cause erratic flight control characteristics.		1) The flight controls should be cycled with hydraulic system pressure through a full stroke at least ten times to bleed air from system. 2) The daily preventive maintenance check, TM 55-1520-210 PMD, Sequence 3.4 requires that the servocylinder be inspected for security.	1) The periodic (100 hour) preventive maintenance check, TM 55-1520-210 PMP should require an operational check of the hydraulic system and a check for air bubbles in the hydraulic oil.

Figure 2 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
		3) Servocylinder mounting Uni-ball Assembly (2, 3, 4 and 7) is: o Galling. o Binding.					3) The servocylinder mount housing (7) contains provisions to lubricate the Uni-ball Assembly (2, 3, 4 and 7) to reduce the possibility of galling and binding. A boot (1) is provided to prevent contaminates from accumulating on the Uni-ball Assembly. (The following is applicable to probable failure causes No. 2 and 3.) The torquing nut (17) is torqued to 200 to 250 inch-pounds and at least 1 tab on lockwasher (18) is bent to torque nut to minimize the possible galling of the bearing (4) and bushing (3) surfaces.	3) The present design concept of the boot (1) is not compatible with hydraulic oil (MIL-H-5606). The boot should be improved using newer materials that are compatible with hydraulic oil and other common types of fluids oils grease. (The following is applicable to probable failure causes No. 2 and 3.) The present design concept of the Uni-ball Assembly (2, 3, 4 and 7) should be improved to use a large one-piece bearing. This design concept eliminates the inherent unloading of the Uni-ball and is described in detail in the Solutions section of this report.
	Excessive feedback to pilot's controls.	1) Air in servo-cylinder. 2) Irreversible valve components are defective.	Possible damage to packings/seals (19, 20) caused by surging hydraulic pressure.	Excessive feedback from servocylinder may cause point loading of flight control rods and bearings resulting in fatigue and wear of these components.	Excessive feedback from servocylinder may cause fatiguing of pilot.		1) The flight controls should be cycled with hydraulic system pressure through a full stroke at least 10 times to bleed air from system.	(The following are applicable to both probable failure causes.) The periodic (100 hour) preventive maintenance check, TM 55-1520-210 PMP should require an operational check of the hydraulic system and a check for air bubbles in the hydraulic oil.

Figure 2 - Continued.

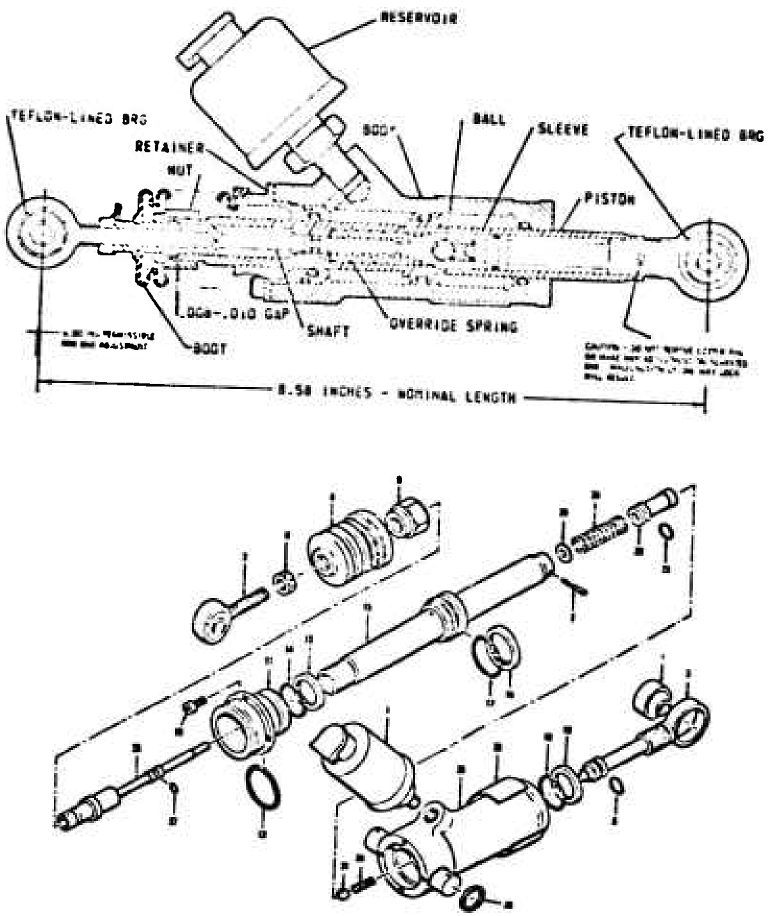

Figure 3. One-Way Locking Actuator.

1. RESERVOIR
2. PIN
3. ROD END
4. ROD END BEARING
5. "O" RING
6. NUT
7. ROD END BEARING
8. BOOT
9. NUT
10. SCREW
11. RETAINER
12. "O" RING
13. TFE CAP SLEEVE
14. "O" RING
15. PISTON
16. TFE CAP SLEEVE
17. "O" RING
18. TFE CAP SLEEVE
19. "O" RING
20. SPRING
21. BALL
22. SLEEVE
23. "O" RING
24. SPRING
25. SEAT
26. SHAFT
27. "O" RING
28. PLATE
29. BUSHING
30. HOUSING

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN-MAINTENANCE COMPENSATING PROVISIONS	REMARK-RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
ONE-WAY LOCKING ACTUATOR UNILOC The Uniloc serves to isolate the rotor longitudinal forces from the Pilot's Cyclic Control Stick. It also serves to dampen sudden and or excessive forces from being applied by the pilot and or copilot to the rotor longitudinal axis. Each part is referenced parenthetically by number to Figure 3.	Uniloc binds in an axial direction.	1) Bushings (29) corroded. 2) Bushing (29) worn excessively. 3) Rod end bearings (7, 4) corroded. 4) Uniloc improperly installed.	Uniloc will become subjected to axial loads (side loading) resulting in excessive wear of the: o Housing barrel (30) surfaces. o Piston (15) surfaces. o "O" rings (14, 17 and 19). o TFE cap sleeves (13, 16 and 18).	The flight control freedom of movement will be restricted along the longitudinal axis.	The helicopter will not respond to normal cyclic forces. Hence, when excessive forces are applied the helicopter may overrespond.		A) Applicable to probable failure causes No. 1 and 3 only. This area is protected from the environmental elements which may contaminate the bushing surfaces. B) Applicable to probable failure causes No. 1, 2, and 3. The flight controls are checked daily for freedom of movement per TM 55-1520-214-20 PMD Sequence 1.10. The Uniloc is inspected during periodic (300 hour) preventive maintenance checks for security and freedom of movement per TM 55-1520-214-20 PMP, Sequence 1.14 and 1.25 respectively.	Applicable to all probable failure causes. The periodic inspection should require the use of a tension meter to determine the actual breakaway friction of the system. This would ensure that the system operates properly. The installation instructions in TM 55-1520-214-20 and -35 should require that the system be operationally checked for breakaway friction by the use of a tension meter.

Figure 4. OH-6A One-Way Locking Actuator (Uniloc) FMEA.

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ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT: SUBASSEMBLY	FAILURE EFFECT: NEXT ASSEMBLY	FAILURE EFFECT: END ITEM		DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
	Uniloc leaks externally.	1) Outer piston (15) surface has worn excessively. 2) Inner barrel wall of piston (15) worn excessively. 3) TFE cap sleeves (13, 18) worn excessively due to defective piston (15) surface finish. 4) TFE cap sleeves (13, 18) worn excessively due to contamination on the piston surface. 5) TFE cap sleeves (13, 18) cold flows. 6) "O" rings (14, 17 and 19) have lost elasticity. 7) "O" rings (14, 17 and 19) have spiraled with dynamic surface. 8) "O" rings 14, 17 and 19) have deteriorated due to inherent heat buildup.	Contamination will accumulate on the piston surface causing increased wear of the piston by the inherent abrasiveness of most contaminants.	Excessive leaking may result in the loss of hydraulic oil disengaging the one-way locking action of the Uniloc Assembly. The TFE lined rod end bearing (4) at the rotor output end may become damaged by abrasive contaminants that have settled in the hydraulic oil.	Loss of hydraulic oil will result in the longitudinal forces of the rotor blade being applied to the pilot's cyclic control stick. Also, quick and excessive inputs by the pilot and or copilot may result in an overcontrol of the helicopter. If the rod end bearing wear is excessive, the flight control linkage play may exceed the allowable limits, resulting in a nonresponsive flight control system. If the rod end bearing becomes contaminated, the breakaway friction may cause a non-esponsive flight control system.		A) (Applicable to probable failure causes No. 1 and 3.) The Uniloc is installed in an area which is isolated from most environmental contamination. The piston surface is chrome plated steel which reduces the tendency of wear on the piston surfaces. The piston surface on the pilot input end has a rubber boot to protect the piston surface from contamination. B) (Applicable to probable failure causes No. 1, 2, 3 and 9.) The Uniloc is checked at 300 hour intervals for evidence of leaking per TM 55-1520-214-20 PMP, Sequence 1.14.	1) The rubber boot to protect the pilot input end is improperly designed to secure the boot. The boot elasticity is insufficient to prevent the boot from slipping past the rod end retaining nut. The result is that contaminants are ingested into the boot area. Normal preventive maintenance checks will not reveal the presence of these contaminants. A) (Applicable to probable failure causes No. 1 and 3.) Pistons should be replated and ground to a 10 to 16 micro-inch RMS finish during overhaul of the Uniloc. B) (Applicable to probable failure causes No. 1, 2, 4, 5, 6, 7, and 8.) Replace present sliding seal Uniloc with an improved Uniloc incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.

Figure 4 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
							C) (Applicable to probable failure causes No. 2, 3, 4, 5, 6, 7 and 8.) The flight controls are checked daily for freedom of movement per TM 55-1520-214-20 PMD, Sequence 1.10.	C) (Applicable to probable failure causes No. 3 and 4.) The present TFE cap sleeve design should be improved to use a graphite or rouge-filled TFE cap sleeve in lieu of the present glass-filled TFE to reduce wear of the moving surface. This concept is described in detail in the Solutions section of this report. D) (Applicable to probable failure causes No. 2, 3, 4, 5, 6, 7 and 8.) An alternative design concept may be the use of the "T" seal with its split backup ring in lieu of the present "O" ring with the TFE cap sleeve. This concept is described in detail in the Solutions section of this report.

Figure 4 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT SUBASSEMBLY	FAILURE EFFECT NEXT ASSEMBLY	FAILURE EFFECT END ITEM	HAZARD CLASS	DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
	Cyclic stick will not stay in position selected by flight crew.	1) "O" rings (17, 23, 27) have lost elasticity. 2) "O" rings (17, 23, 27) have spiraled with dynamic surface. 3) "O" rings (17, 23, 27) have deteriorated due to inherent heat buildup. 4) Inner barrel wall of piston (15) worn excessively. 5) Sleeve (22) surface has worn excessively. 6) Check valve ball (21) is corroded. 7) Check valve spring (20) has insufficient tension.	Spiraling and/or contamination of the "O" rings may damage the dynamic surfaces.	Spiraling of the "O" rings may jam the control linkage.	The flight crew may fatigue from the constant rotor beat being applied to the cyclic control stick. The helicopter may be overcontrolled by flight crew inputs		(Applicable to probable failure causes No. 1, 2, 3 and 4.) The Uniloc is checked for freedom of movement at daily and periodic (300 hour) inspections per TM 55-1520-214-20 PMD Sequence 1.10 and -20 PMP, Sequence 1.25, respectively.	[illegible] Normal preventive maintenance checks will not readily reveal such internal failures. The periodic inspection should require the operational check-out with the helicopter in the powered-up engine and rotor operating condition. A (Applicable to probable failure causes No. 1, 2, 3, 4, 5 and 6.) Normal preventive maintenance checks will not readily reveal such internal failures. The periodic inspection should require the use of tension meters and the analysis of hydraulic oil. B (Applicable to probable failure causes No. 1, 2, 3, and 4.) Replace present sliding seal hydraulic servocylinder with an improved servocylinder incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.

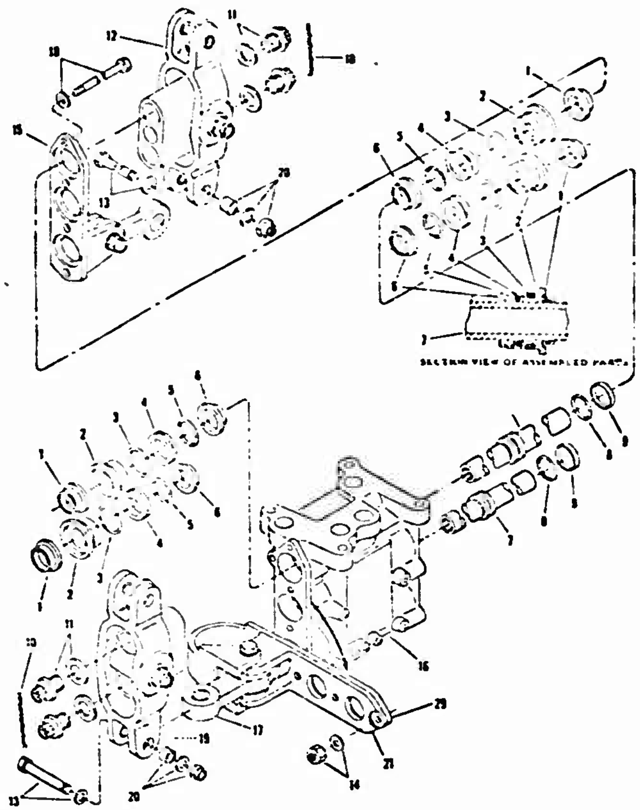
Figure 4 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								C Applicable to probable failure causes No. 1, 2, 3 and 4. An alternative design concept may be the use of the T seal with its split back up ring in lieu of the present "O" ring with the TFE cap sleeve. This concept is described in detail in the Solutions section of this report.
	Oversensitive to pilot's input forces.	1) Override spring (24) has lost its tension. 2) Check valve spring (20) has lost its tension. 3) Housing barrel (30) wall is worn excessively. 4) Check valve ball (21) is contaminated. 5) "O" ring (17) with TFE cap sleeve (16) has deteriorated.	"O" ring (23) may wear excessively.	Flight controls would be oversensitive.	The flight crew may fatigue from the constant rotor beat being applied to the cyclic control stick. The helicopter may be overcontrolled by flight crew inputs.		Applicable to all failure causes. The Uniloc is checked for freedom of movement at the daily and periodic (300 hour) preventive maintenance inspections per TM 55-1520-214-20 PMD, Sequence 1.10 and -20 PMP, Sequence 1.25.	5 Replace present sliding seal hydraulic Uniloc with an improved Uniloc incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report. An alternative design concept may be the use of the T seal with its split back up ring in lieu of the present "O" ring with the TFE cap sleeve. This concept is described in detail in the Solutions section of this report.

Figure 4 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								(Applicable to all probable failure causes.) Normal preventive maintenance inspections will not readily reveal such oversensitivity. The periodic inspection should require the use of tension meters to determine system sensitivity.
	Cyclic flight controls will not lock in the position selected by the flight crew.	1) Check valve spring (20) has lost its tension. 2) Housing barrel (10) wall is worn excessively. 3) "O" ring (17) with TFE cap sleeve (16) has deteriorated. 4) Check valve ball (21) is contaminated.	Check valve ball (21) may be damaged.	Flight controls will not lock in selected position.	The flight crew may fatigue from the constant rotor beat being applied to the cyclic control stick. The helicopter may be overcontrolled by flight crew inputs.		(Applicable to all probable failure causes.) The Uniloc is checked for freedom of movement at the daily and periodic (300 hour) preventive maintenance inspections per TM 55-1520-214-20 PMD, Sequence 1.10 and -20 PMP, Sequence 1.25.	(Applicable to probable failure causes No. 2 and 3.) Replace present sliding seal hydraulic servocylinders with an improved servocylinder incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.

Figure 4 - Continued.



1. PISTON SCRAPER
2. SHOULDER BEARING
3. ROUND PREFORMED PACKING
4. DELTA-SHAPED PERFORMED PACKING
5. ROUND PREFORMED PACKING
6. PACKING RETAINER
7. PISTON
8. ROUND PREFORMED PACKING
9. FLAT PREFORMED PACKING
10. LOCKWIRE
11. BOLT AND WASHER
12. OUTPUT LEVER AND PIVOT BLOCK
13. BOLT AND WASHER
14. NUT AND WASHER
15. OUTPUT END PLATE
16. HOUSING
17. DOUBLE ROD END BEARING
18. LONG BOLT AND WASHER
19. INPUT LEVER AND PIVOT BLOCK
20. NUT, WASHER, AND BUSHING
21. INPUT END PLATE (ROTATED)
22. INPUT END PLATE (REMOVED)
23. SHOULDERED BUSHING
24. NUT AND WASHER
25. SPECIAL WASHERS
26. CLEVIS AND CONTROLLER VALVE
27. BOLT
28. PREFORMED PACKING (DUST SEAL)
29. VALVE AND SPRING ASSEMBLY

Figure 5. CH-47 Stick-Boost Dual Actuating Cylinder (Exploded View).

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
STICK-BOOST DUAL ACTUATING CYLINDER Four stick-boost dual actuating cylinders are used in the flight control system. They serve to transmit the control forces from the cockpit controls to the forward upper and aft flight controls. The four cylinder controls are for pitch, roll, yaw and thrust. Each part is referenced parenthetically by number to Figure 5.	Binding.	1) Excessive side loading caused by installation error. 2) Contamination captured between housing wall (16) and piston (7). 3) Deformed wall (16) or piston (17) surface caused by corrosion or contamination. 4) Excessive vibration resulting in bearing (2) failure of piston plating surface, releasing particles and providing excessive play.	Hydraulic oil accumulation on piston (7) will cause contamination to accumulate and accelerate the wear of: o Piston (7) surfaces. o Housing (16) barrel surfaces. o Rod end (1) scrapers. o "O" ring seal (3, 5). o "Δ" shaped packing (4). o Shoulder bearing (2).	Rotor assembly cannot respond accurately to control system input for swiveling and pivoting.	Helicopter fails to respond accurately to pilot system command requirements.		A) (Applicable to probable failure causes No. 1 and 2.) Unresponsive or "sticky" controls can be overridden to land a helicopter safely. B) (Applicable to probable causes No. 1, 2 and 4.) Control system checkout per TM 55-1520-209 PMD requires that controls be smooth and responsive prior to flight.	(Applicable to probable failure causes No. 1, 2, and 3.) Replace present sliding seal hydraulic cylinder with an improved cylinder incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.
	Leaking excessive.	1) Broken seal packing (3, 4, 5). 2) Seal packing (3, 4, 5) worn excessively. 3) Broken housing (16).	Hydraulic oil accumulation on piston (7) will cause contamination to accumulate and accelerate the wear of: o Piston (7) surfaces. o Housing (16) barrel surfaces. o Rod end (1) scrapers. o "O" ring seal (3, 5).	Failure to either swivel or pivot forward or aft rotor assembly if both cylinders fail at the same time.	Critical to helicopter only if both cylinders fail at the same time to respond during maneuvers other than level flight. Serious loss of hydraulic fluid. Fire hazard from hydraulic fluid.		1) Tolerances between piston and housing are such that the cylinder will respond slowly and with less pressure as the system loses pressure, allowing time for automation. 3) Redundancy of 2 hydraulic cylinders reduce helicopter hazard to a minimum.	1) A catastrophic failure of a seal would result in quantities of spilled hydraulic fluid. However, the probability that the second cylinder fails simultaneously is very small. 3) Dye penetrant or magnetic particle inspections should be performed on all cylinder housing during manufacture and overhaul.

Figure 6. CH-47 Stick-Boost Dual Actuating Cylinder FMEA.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								A) (Applicable to probable failure causes No. 1 and 2.) Replace present sliding seal hydraulic cylinder with an improved cylinder incorporating a non-sliding seal. This design concept is described in detail in the Solutions section of this report. B) (Applicable to probable failure causes No. 1 and 2.) An alternative design concept may be the use of the "T" seal with its split back up ring in lieu of the present "O" ring with the TFE cap sleeve. This concept is described in detail in the Solutions section of this report.
	Leaking, moderate to slight.	1) Worn "O" ring seal packing (3, 4, 5). 2) Worn Δ shaped packing (4). 3) Hydraulic system pressure is excessive.	Hydraulic oil accumulation on piston (7) will cause contamination to accumulate and accelerate the wear of: o Piston (7) surfaces. o Housing (16) barrel surfaces.	Reduction in response for pivoting and swiveling only if remaining cylinder also leaks at the same rate.	Helicopter fails to respond accurately to pilot system commands.		(Applicable to probable failure causes No. 1, 2, and 3.) Redundancy of 2 hydraulic cylinders reduce helicopter hazard to a minimum.	

Figure 6 - Continued.

ITEM/FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT				DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
								A) (Applicable to probable failure causes No. 1, 2 and 3.) Replace present sliding seal hydraulic cylinder with an improved cylinder incorporating a non-sliding seal. This design concept is described in detail in the Solutions section of this report. B) (Applicable to probable failure causes No. 1 and 2.) An alternate design concept may be the use of the "T" seal with its split backup ring in lieu of the present "O" ring with the TFE cap sleeve. This concept is described in detail in the Solutions section of this report.
	Fails to respond to pilot's input.	1) Clogged orifice resulting in reduced hydraulic pressure. 2) Broken housing (16) case.	Lack of adequate hydraulic oil will accelerate the wear of: o Piston (7) surfaces. o Housing (16) barrel surfaces.	Failure to either pivot or swivel forward or aft rotor assembly only if both cylinders fail simultaneously.	The helicopter will not respond to normal flight control input forces.		1) Filters reduce potential for clogged orifice. 2) Redundancy of 2 hydraulic cylinders reduce hazard to helicopter to a minimum.	1) Replace present sliding seal hydraulic cylinder with an improved cylinder incorporating a nonsliding seal. This design concept is described in detail in the Solutions section of this report.

Figure 6 - Continued.

ITEM FUNCTION	FAILURE MODE	PROBABLE FAILURE CAUSE	FAILURE EFFECT			HAZARD CLASS	DESIGN/MAINTENANCE COMPENSATING PROVISIONS	REMARKS RECOMMENDATIONS
			SUBASSEMBLY	NEXT ASSEMBLY	END ITEM			
			o Rod end (1) scrapers. o "O" ring seal (3, 5). o Δ shaped packing (4). o Shoulder bearing (2).					2) Dye penetrant or magnetic particle inspections should be performed on all cylinder housings during manufacture and overhaul.

Figure 6 - Continued.

REQUIREMENTS, PROCEDURES, AND PRACTICES

An analysis was conducted in the areas of requirements, procedures, and practices as a part of this study to identify the underlying basis of those servocylinder deficiencies that result in the lower than desired availability of U.S. Army helicopters. The basic areas analyzed were:

1. Design Requirements
2. Quality Assurance Provisions
3. Maintenance Procedures and Practices
4. Test Requirements and Procedures

Each of these requirements, procedures, and practices was then reviewed as to its ability to satisfy the basic performance requirements defined in MIL-C-5503C ("General Requirements for Aeronautical Hydraulic Actuating Cylinders") for the cylinders and in MIL-V-7915 ("Valves, Hydraulic, Directional Control, Slide Selector") for the mechanical hydraulic power control valves. Whenever control documentation anomalies were found, they were documented along with their potentially resulting failure modes and the possible impact upon the performance of the hydraulic servocylinder in the U.S. Army usage environment.

Table III presents an overview of failure modes induced by deficiencies in requirements, procedures and practices. Identified for analysis during this program were 24 possible contributors to premature failure of systems equipments and components. Nineteen of these were considered as probable contributors to the leaking failure mode. At the other extreme, erroneous removal (no failure) is considered to result only from maintenance procedure and practice deficiencies.

DESIGN REQUIREMENTS ANALYSIS

This analysis was performed to evaluate the cause-and-effect relationship between the failures and the design requirements and component procurement process used by the U.S. Army. The following were investigated:

1. Specification control documents and drawings
2. Component selection criteria
3. Military specifications and standards

TABLE III. FAILURE MODES INDUCED BY DEFICIENCIES IN REQUIREMENTS, PROCEDURES AND PRACTICES

Requirements, Procedures and Practices	Leaking	No Failure (Erroneous Removal)	Internal Failure	Excessive Wear
Design Requirements:				
Specification Control Documents and Drawings	X	-	-	X
Component Selection Criteria	-	-	X	-
Military Specifications and Standards	X	-	-	-
Design Requirements to Eliminate Induced Failures	X	-	-	-
Contract Specifications	X	-	-	-
Quality Assurance Provisions:				
Vendor Manufacturing Quality Control and Shipping Inspections	X	-	-	-
Airframe Manufacturer Receiving Inspection	-	-	X	-
Initial Installation Procedures	X	-	X	-
Functional Test Procedures	X	-	X	-
Mandatory Inspection Points	X	-	X	-
Component Sampling Procedures	X	-	X	-

TABLE III - Continued

Requirements, Procedures and Practices	Leaking	No Failure (Erroneous Removal)	Internal Failure	Excessive Wear
Maintenance Procedures and Practices:				
Maintenance Manuals	X	-	-	X
Periodic Inspections	X	-	-	-
Shelf Life Considerations	-	-	-	X
Failure Criteria and Detection	-	X	-	-
Maintenance Personnel Skill Level, Qualifications, and Training	X	X	-	-
Special Tool Requirements	-	-	-	-
Component Accessibility	X	-	-	-
Test Requirements and Procedures:				
Environmental Tests and Procedures	X	-	-	-
Systems Compatibility Testing Requirements and Procedures	X	-	X	-
Qualification Test Requirements and Procedures	X	-	X	-
Flight Test Plan and Procedures	X	-	X	-
Service Tests, Plans, and Procedures	X	-	X	-
Acceptance Tests Procedures and Results	X	-	-	X

4. Contract specifications

5. Design requirements at the component level

6. Degree of compliance to the design requirements

Each of these areas was analyzed separately to determine if the U.S. Army operational and environmental requirements and constraints were adequately considered and incorporated.

Specification Control Documents and Drawings

The specification control documents and drawings for U.S. Army hydraulic servocylinders and their constituent components are the basic guidelines used to control the design and procurement of hardware.

These documents were analyzed to determine the following (see Table IV):

1. Were applicable documents adequately incorporated?

2. Were U.S. Army operational envelope (environmental) requirements adequately incorporated?

3. Did drawings include applicable tolerances that were realistic?

4. Were reliability and maintainability requirements stated or provided?

Applicable Requirements Documents

The analysis of the drawings summarized in Table IV reveals clear deficiencies in the incorporation of necessary requirements. In no case did these drawings refer to such controlling documents as the following:

1. MIL-C-5503C, "General Requirements for Cylinders, Aeronautical, Hydraulic Actuating"

2. MIL-V-7915, "Valves; Hydraulic, Directional Control, Slide Selector"

TABLE IV. SAMPLE OF SPECIFICATION CONTROL DOCUMENTATION DRAWING REVIEW

Drawings Reviewed	Applicable Documents Incorporated	Operational/ Environmental Requirements Stated	Drawing Tolerances Stated	Reliability and Maintainability Requirements Stated
Hydraulic Research 105875	No	Operational Only	Yes	No
Hydraulic Research 41000311/ 41000310	No	Operational Only	Yes	No
Conair A1660-3	No	No	No	No
Conair A1660-5	No	No	No	No
Conair A1660-23	No	No	No	No
Conair A1660-27	No	No	No	No
Sargent Bros. SGT 220	No	No	No	No

U.S. Army Operational Envelope

The drawings listed in Table IV were analyzed to determine if they imposed either operational or environmental requirements down to the component parts level. The only requirements found were related to the stroke length of the actuator. These deficiencies introduce gaps in verified performance capabilities that allow the hydraulic servocylinder to fail to meet the operational and environmental requirements. These anomalies also result in equipment malfunctions, decreased helicopter availability and increased maintenance costs. Subsequent equipment modifications may be necessary if the anomaly is sufficiently serious. This situation also results in the likelihood of premature removal of the equipment for such failure modes as leaking.

Tolerance Requirements

Equipment tolerances are essential for the specific application for which the unit is being procured. MIL-STD-100A (Engineering Drawing Practices) and USAS-114.5, Y14.5 1966 (Dimensioning and Tolerances for Engineering) provide the standards and provisions for the incorporation of such tolerances. However, the helicopter and its constituent flight control subsystem determine the specific tolerances required for the hydraulic servocylinder. Tolerances that are too stringent or too loose result in equipment performance problems. Tolerances that are too stringent result in increased friction and hysteresis induced heat buildup with resultant premature wearout of such components as "O" ring seals/packings. Tolerances that are too loose result in premature leakage of hydraulic oil due to the increased tolerances. Both of these conditions result in higher life-cycle cost, the former by increased engineering, manufacturing and rejection rate costs and the latter by increased maintenance and logistics costs. Tolerance buildup problems result in either the lack of adequate sealing surface or excessive friction. Both of these problems result in premature leaking of servocylinders. The excessive friction may result in actuator binding or in erratic or stiff flight controls.

The summary of the drawings analysis shown in Table IV reveals that some drawings did not incorporate reasonable tolerances. This is probably due to MIL-STD-100A and USAS-114.5 1966 not being imposed by the specification control drawings during the initial design phase.

Reliability and Maintainability Requirements

The documentation analyzed did not contain reliability and maintainability quantitative or qualitative requirements. This results in a high likelihood of occurrence of certain failure modes, especially those associated with premature wearout or improper maintenance. These failure modes usually are binding or leaking.

Component Selection Criteria

Component selection criteria provide the basis for decreased life-cycle cost with relationship to the desired availability. That is, the criteria established for selecting components must consider both the desired availability and life-cycle cost constraints. Most components used in hydraulic servocylinders are governed by military specifications. MIL-H-8875C, "General Specification for Hydraulic System Components, Aircraft and Missiles," delineates the requirements for the constituent components for hydraulic systems. Also, specifications such as MIL-C-5503 delineate the requirements for specific equipment.

The analysis of this section demonstrates that the requirements of MIL-H-8775C or MIL-C-5503C were not imposed in the original specification control documentation used to procure various hydraulic system components. Therefore, there is no adequate assurance that components presently being used within existing inventory helicopter hydraulic systems meet military design performance requirements.

Military Specifications and Standards

The various military specifications and standards which govern the design and manufacture of hydraulic servocylinders were analyzed to determine compliance with MIL-STD-490. Figure 7 presents the provisions of MIL-STD-490 as related to helicopter hydraulic servocylinder specifications.

These requirements and provisions must be considered in the design and procurement of equipment to ensure that the life-cycle cost of the equipment will be minimal in the U.S. Army operating environment.

The general specifications specifically governing hydraulic servocylinders are MIL-C-5503C, MIL-V-7915, MIL-G-5514F, and MIL-S-5049B. As shown in Table V, these specifications and those relating to flight control systems contain insufficient requirements to control the life-cycle cost of the hydraulic servocylinders. The noted specifications were written primarily for fixed-wing aircraft and for U.S. Navy and U.S. Air Force operating environments. Consequently,

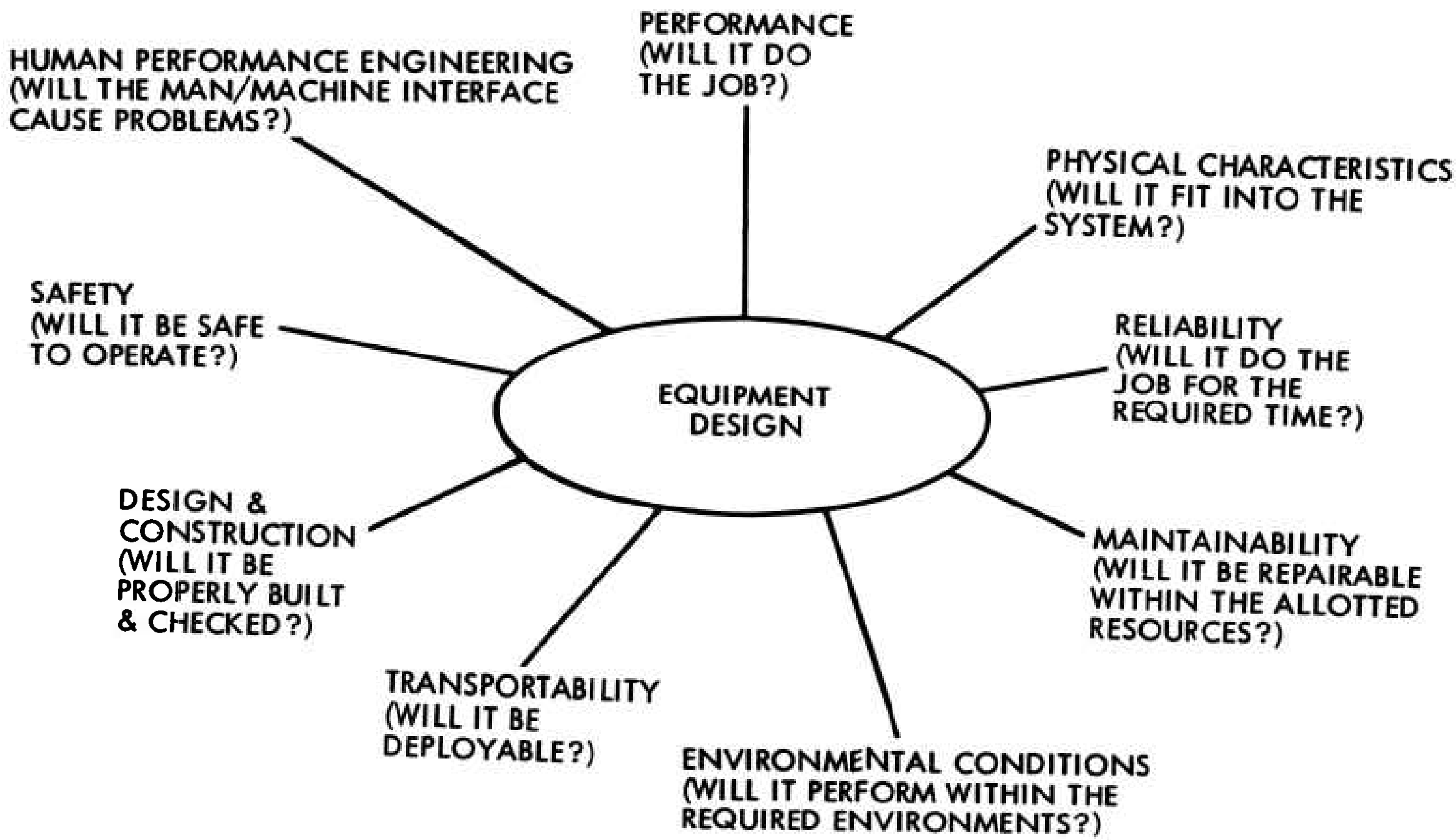


Figure 7. Provisions of MIL-STD-490 as Related to Helicopter Hydraulic Servocylinder Specifications.

TABLE V. ADEQUACY OF MILITARY SPECIFICATIONS TO BASELINE REQUIREMENTS

Specification No. / Baseline Requirements	MIL-C-5503C General Requirements for Cylinders, Aeronautical, Hydraulic Actuating	MIL-V-7915 Valves; Hydraulic, Directional Control, Slide Selector	MIL-S-5049 Hydraulic Piston Rod Scrapers	MIL-H-5440E Hydraulic Systems, Aircraft Types I and II: Design, Installation and Data Requirements	MIL-F-9490F General Specification for Flight Control Systems - Design, Installation and Test of Piloted Aircraft	MIL-G-5514F General Requirements for Gland Design, Packings, Hydraulic
1 Item Description	Yes	Yes	Yes	Yes	Yes	Yes
2 Characteristics						
2.1 Performance	Yes	Yes	Yes	Not required for helicopter or U.S. Army usage	Yes	Yes
2.2 Physical Characteristics						
a. Weight	Not Required	Yes	Not Required	Not Required	Not Required	Not Required
b. Dimensions	Not Required	Not Required	No	Not Required	Not Required	Yes
c. Transport and Storage Requirements	Yes	No	Yes	Not Required	Not Required	No
d. Durability Factors	Yes	No	No	No	Yes	No
e. Health and Safety Criteria	No	No	No	No	No	No
f. Vulnerability	No	No	No	Yes	Yes	No
2.3 Reliability	No	No	No	No	Yes	No
2.4 Maintainability	No	No	No	No	Yes	No
2.5 Environmental Conditions	Inadequate	Inadequate	No	No	No	No
2.6 Transportability	No	No	No	Not Required	Not Required	No
2.7 Design and Construction						
2.7.1 Materials and Processes	Yes	Yes	Yes	Yes	Yes	Yes
2.7.2 Electromagnetic Interference	Not Required	Not Required	Not Required	Not Required	Yes	Not Required
2.7.3 Identification and Marking	Yes	Yes	No	No	Yes	No
2.7.4 Workmanship	Yes	Yes	Yes	No	Yes	No
2.7.5 Interchangeability	Yes	Yes	No	No	Yes	No
2.8 Safety	No	No	No	No	Yes	No
2.9 Human Performance	No	No	No	No	Yes	No

these documents do not consider either the helicopter or the U.S. Army operating profiles. This results in an increased likelihood of premature failures. An example of a deficiency in a specification failing to meet the operational requirements of the Army is MIL-S-5049B. This specification is applicable to the design of piston rod end scrapers, which keep contaminants from being ingested into the hydraulic servocylinders. However, recent tests using Vietnam coral dust revealed that none of the rod end scrapers completely eliminated the ingestion of this minute but very abrasive substance. The resultant anomalies in the equipment performance were discussed under the heading of Specification Control Documents and Drawings.

The failure mode that is most likely to occur as a result of inadequate military specifications is leaking. This judgment is based upon the rationale that the sealing requirements of servocylinders are the most critical design element and thus the most likely to fail if specifications are inadequate.

Contract Specifications

Interviews with various helicopter and servocylinder manufacturers revealed the absence of a formal set of performance requirements.

The main vehicle used by the helicopter manufacturers to define the requirements for their vendors is the specification control drawing. These drawings were reviewed and found not to contain U.S. Army helicopter operational requirements. To minimize currently experienced hydraulic servocylinder failure modes, sufficient Army helicopter operational requirements must be included in order that the designer can design to the projected operating environment.

When realistic requirements in the contract specifications are imposed on the contractor, the likelihood of failure modes such as leaking is minimized. Servocylinder hydraulic leaks are usually the result of inadequate parameters being supplied to the designer.

Design Requirements To Eliminate Induced Failures

The most probable failure causes listed in the Failure Modes and Effects Analysis section of this document for external leakage of hydraulic fluid are as follows:

1. Side loading due to transverse vibrations
2. Worn rod end scrapers

3. Worn packings/seals

4. Packings/seals damaged during installation

5. Worn piston rod surfaces

6. Improper filtration of hydraulic oil

7. Worn TFE cap sleeves

These are all possible causes of induced servocylinder failures. Source control drawings generally call out the specific vendor part number of the components required for the servocylinder. As shown in the specification control documentation analysis, these documents did not impose the required military specification and military standards on the servocylinder design for use on Army helicopters.

Failure induced by side loading could be prevented by imposing design requirements on flight control systems such that all of the component parts, i.e., servocylinders, are compatible with the helicopter operational requirements. However, the source control drawings did not impose such a system compatibility requirement on the servocylinder design.

Excessive wear of rod end scrapers, packings/seals, TFE cap sleeves and piston rod surfaces is part of a vicious circle which can be prevented in a number of ways. The premature wear of any of these components will allow seepage of hydraulic oil that will accumulate on the piston rod surfaces and attract contamination. This in turn will accelerate the wear of these components, which increases the hydraulic seepage into the category of a hydraulic leak (more than 1 drop in 200 cycles). One major design innovation that should be imposed on the servocylinder is in the area of allowable leakage. MIL-C-5503C allows 1 drop of hydraulic fluid per 25 cycles; this also is the reject criterion during maintenance actions. This is but one example of inadequate design requirements inducing failures of hydraulic servocylinders.

Inadequate filtration of hydraulic oil is a cause of failure which could be prevented by insuring that adequate preventive maintenance procedures are imposed with respect to filtration. The design of the helicopter must consider the frequency with which hydraulic filters must be checked and replaced. The filters also should be designed such that the indicator button cannot be reset without replacing the filter. Hydraulic servocylinder tolerances must also consider hydraulic system filtration to insure that adequate filtration exists to prevent failures induced by allowable system contamination.

The basic design requirements must be functionally representative of the operational and environmental requirements. That is, the U.S. Army requirements for the helicopter operations must be the basis for establishing a typical mission profile. This mission profile, with the required availability and life-cycle cost considerations included, should then be utilized in determining design constraints for the hydraulic servocylinder and its constituent components. This investigation did not uncover design requirements specifically tailored toward the reduction of failures. Inherent or induced failures such as leaking usually occur when either of these parameters (helicopter availability or life-cycle costs) is either inadequately examined or not considered during the design phase. When these potential failures are not eliminated during the conceptual and/or design phases, lower helicopter availability will result.

Degree of Compliance to the Design Requirements

The design requirements presently being imposed upon the airframe and component manufacturers are of little value to the Army because of its present operational environments. The design requirements that are provided by MIL-C-5503, MIL-V-7915, MIL-G-5514F, and MIL-S-5049 were primarily intended for U.S. Air Force and U.S. Navy fixed-wing aircraft. It appears the manufacturers do comply with those requirements that are directly imposed upon them. Those requirements that could reasonably be inferred by type of item being procured and from the known operational environment involved are usually not imposed on the design in order to reduce the initial procurement costs. The most obvious of these was indicated by most U.S. Army servocylinder suppliers. If suppliers design to requirements more stringent than those imposed by the control or military specifications, they become noncompetitive on cost alone. This objection could be overcome by imposing realistic requirements as dictated by the operational environment and by using life-cycle cost, not initial cost, as the primary cost measuring tool.

Without a Quality Assurance (QA) program, there is no certification or documentation to indicate compliance with specification control documents and drawings, military specifications, on contract specification design requirements to eliminate induced failures. No evidence of component selection criteria or overall military specification for the hydraulic servocylinder was found while reviewing specification control drawings.

Many of the problems with current-inventory helicopters were the result of the U.S. Army requirement for a large quantity of helicopters in a short period of time for use in Southeast Asia. As a consequence, design concepts for commercial helicopter applications were used for military versions of similar helicopters. Because of this urgent need for helicopters, availability of similar commercial design concepts and competition for available funds, numerous exceptions to military specifications were granted. While this procedure was an acceptable standard under the above conditions, definitive steps must be taken in the future to insure that all operational requirements are incorporated into the design of military equipment.

The benefits to be derived from incorporating all Army operational requirements into the basic design are as follows:

1. Decreased failure rates
2. Decreased maintenance man-hours
3. Increased availability
4. Decreased logistics requirements
5. Lower life-cycle cost for the helicopter system

QUALITY ASSURANCE

This analysis was performed to evaluate the cause-and-effect relationship between the failures in the hydraulic servocylinders and the quality assurance deficiencies. The areas that were specifically investigated are as follows:

1. Vendor quality control and shipping inspection
2. Receiving inspection
3. Initial installation procedures
4. Functional test procedures
5. Mandatory inspection points
6. Component sampling procedures
7. Degree of compliance to the QA requirements

Vendor Quality Control and Shipping Inspection

This study revealed that only the most rudimentary quality assurance procedures are being used by the vendors or U.S. Army depot organizations. A comprehensive QA Program Plan did not appear to be in existence at any of the vendors involved. Some vendors did display QA procedures for certain phases of their operation, but these procedures did not indicate the existence of a general or specific QA Program Plan. For example, Leakage Test Procedures required only a few cycles for certification. None of these procedures were comprehensive enough to follow the product from raw material or component part reception inspections through packing and shipping inspections.

In fact, none of the procedures reviewed incorporated either receiving or shipping inspections. Recommendations to attain the necessary design verification for future procurements are presented in the Revisions section of this report.

The failure modes most likely to occur as the result of inadequate vendor QA procedures are leaking due to damaged gland seals or scrapers, longitudinal scratches on the piston or barrel surfaces, and surface finishes out of tolerance so that an effective seal cannot be maintained. Also, improper packaging could cause damage to piston surfaces, causing leakage past the gland seals.

Airframe Manufacturer Receiving Inspection

Vendors' parts received by airframe manufacturers are not usually inspected. Hydraulic servocylinders are normally manufactured and functionally inspected by the vendors. They are received and installed upon the helicopters without any additional QA inspections being performed. Operational and mechanical inspections are next performed upon a completed helicopter. This identical procedure is also used by Army overhaul facilities such as ARADMAC. The airframe manufacturers did indicate that received and/or source inspections would be instituted if recurring failures of a specific design are noted during the completed helicopter QA inspections.

It appears from this analysis that either the airframe manufacturers do not feel that the hydraulic servocylinder failures are significant enough to institute receiving inspections, or that receiving inspection benefits would not appreciably enhance the overall operational performance of the servocylinder. The operational checks of the servocylinder after installation could be constituted as a receiving inspection under the rationale previously discussed. However, if the vendor is not required to perform quality control inspections prior to shipment, the airframe manufacturer should institute some form of sampling technique to inspect the received servocylinders.

The most prevalent failure mode that could be reduced or eliminated is binding, where damage during transit has caused the actuator to be bent or jammed. This type of damage usually results from improper packing for shipment from vendor to airframe manufacturer. Therefore, whenever improper packaging is noted, a reviewing operational inspection should be required prior to installation in the helicopter.

Initial Installation Procedures

The individual helicopter manufacturers visited during this study did not provide any evidence of the existence of formal initial installation procedures for hydraulic servocylinders.

The initial installation procedure deficiencies that presently exist within the U.S. Army are developed more specifically in the analysis of the maintenance manuals. The required maintenance verification necessary to validate the adequacy of the servocylinder installation by Army maintenance personnel is also discussed in the analysis of maintenance manuals.

The servocylinder failure modes that can be attributed to this lack of adequate installation procedures are as follows:

1. Air in the hydraulic system
2. Leakage around gland seals
3. Misalignment
4. Interference
5. Improper torquing of attach points
6. Safety wiring of nuts and bolts
7. Excessive friction between gland seals and piston/barrel surfaces

Functional Test Procedures

Functional testing was found to exist in a very rudimentary form at some of the hydraulic servocylinder manufacturers. The functional test usually involved cycling the servocylinder for a fixed number of cycles and checking for leaks. In no case were the servocylinders loaded. The U. S. Army maintenance personnel at both the Organizational and Depot (at the flight line and/or assembly area) maintenance levels do not attempt to check out a servocylinder prior to installation in a helicopter.

Depot overhaul (shop) maintenance procedures do require a functional test of the hydraulic servocylinder after overhaul. The test procedures used at ARADMAC for functional testing of hydraulic servocylinders were very specific and detailed. However, tests for leakage allow 1 drop in 25 cycles, which is considered to be inadequate as a leakage accept/reject criterion.

The performance of realistic functional tests prior to installation results in detection of leaks and binding between the piston and the barrel. The result is increased helicopter availability.

Mandatory Inspection Points

Because of the inherent design and interface of hydraulic servocylinders with other systems and components, certain inspection criteria should be clearly enumerated on QA inspection sheets for helicopter installation. Also, certain inspection criteria and check points must be enumerated on QA inspection sheets for use by servocylinder manufacturers.

As discussed in the Maintenance Analysis portion of this report, maintenance verification provisions are not imposed by the applicable technical manual. Instead, they are indirectly imposed by TM38-750, the Army Maintenance Management System (TAMMS).

The failure modes that would be minimized by QA and maintenance verification inspections of mandatory points are as follows:

1. Binding of the servocylinder due to improper installation
2. Leakage around piston seals due to oversized tolerances and/or contamination of piston rod surfaces

Component Sampling Procedures

Component sampling procedures for helicopter servocylinders are not specifically spelled out by the manufacturers and/or the Army. The seal manufacturers do some sampling on their own. The degree and comprehensiveness are functions of the particular seal manufacturer's self-imposed stardards. When military standard seals are used, that standard specifies the sampling procedures that must be adhered to.

However, no evidence of the sampling procedures as delineated in the applicable military specification was found at these seal manufacturers.

Component sampling is instituted by servocylinder manufacturers only when they find that a particular supplier's parts are causing recurring problems.

The failure modes that would be minimized by component sampling procedures are as follows:

1. Leaking caused by inadequate sealing surfaces
2. Binding caused by excessive friction or mechanical tolerance buildup

Degree of Compliance to the Quality Assurance Requirements

The vendors contacted have not had quality control or shipping inspection procedures formally imposed upon them by helicopter manufacturers. Coupled with this is the absence of a military specification requirement for a thorough receiving inspection by the airframe manufacturer.

It may be that only the highest quality commercial parts are being used, but this does not mean that these components meet or exceed the quality required by the military specification. To demonstrate that commercial and military standard parts reflect the quality required by the applicable military specification, such requirements as component sampling and functional tests must be performed. There was some evidence of sampling for the purpose of QA by the gland seal vendors. No data were available to indicate the level of quality or the degree of conformity to the military specification requirements.

Neither installation procedures, mandatory test procedures, nor functional test procedures were furnished by the airframe manufacturers. They claim to have such procedures and to use these procedures, but, because of proprietary rights, they could not divulge them. Mandatory testing points for use by U.S. Army maintenance verification personnel are indirectly set forth in TM38-750 but not by the applicable TM (i.e., TM55-1520-210-20), so Army facilities could hardly be expected to comply.

MAINTENANCE PROCEDURES AND PRACTICES

The analysis in this section identifies the problem areas associated with the following:

1. Technical maintenance manuals
2. Periodic preventive maintenance inspection cards
3. Component shelf life
4. Failure criteria and detection methodology
5. Maintenance skills and training
6. Special equipment and tool requirements
7. Component accessibility

Also presented is the degree of compliance with existing technical references when performing each level of maintenance on U.S. Army helicopter flight control hydraulic servocylinders.

Maintenance Manuals

The various manuals which govern the maintenance, inspection, replacement, and checkout of hydraulic control system servocylinders were reviewed and analyzed to determine their effect upon hardware performance. The manuals were examined to determine whether:

1. Applicable documents are adequately considered for technical reference.

2. Assignment of Level of Repair (LOR) is responsive to hardware operational requirements and constraints.

3. The applicable subsystem to be repaired is adequately described.

4. All adjustment procedures, including tolerances, are provided.

5. Material/manpower requirements are specified, including special tools and test equipment.

6. Skill levels required to perform assigned maintenance tasks are given.

The general tone of a technical manual, as well as the frequency of reference to other manuals, can encourage or discourage its use as a tool in maintenance procedures. Reliance on practical experience rather than "going by the book" often causes many of the maintenance-induced failure modes such as leaking or binding in servocylinders.

Level of Repair

The maintenance level for disassembly, repair, and test of hydraulic servocylinders requires a "shop" environment with special tools, clean rooms, and pressure test benches. This is clearly beyond the possible organizational level application of effort. TM55-1520-210-34 (Direct Support/General Support [DS/GS]) addresses shop level maintenance, but does not include overhaul and test procedures for hydraulic servocylinders within the manual. The mechanic is required to refer to TM55-1650-312-40 for these procedures.

Repair of hydraulic servocylinders in the Army is depot-level maintenance, according to interviews in the field. However, "leakage only" failures could be handled at DS/GS level if there is no metal damage. According to the MISS data, 45 percent of servocylinder (UH-1H) removals occur within the first 100 flight hours after servocylinder overhaul. This points to overhaul induced failures leading to premature leaking, which accounts for the early failures documented in the MISS report.

Subsystem Description

The DS/GS maintenance manual does not offer any functional description or mechanical purpose of the system or subsystem. While this omission may not be significant to performance of the more experienced mechanic, the performance of the less experienced mechanic may be adversely affected.

Lack of technical information such as component location, function, part numbers, etc., will contribute to any of the maintenance-induced failure modes (refer to Table III).

Adjustment Procedures

The only adjustment or tolerance data included in the maintenance manuals are torque and pressures. Clearance and wear tolerance information is not presented. This lack of information can be the indirect cause of the excessive-wear failure mode.

Materiai/Manpower Requirements

Materials are specified only as included in a maintenance procedure. Neither organizational nor DS/GS maintenance manuals specify manpower requirements.

Indirectly, omission of manpower requirements can dilute the overall maintenance effort due to lack of management visibility of the continuing workload. This affects helicopter availability and all maintenance-related failure modes.

Skill Level Requirements

Skill levels required to perform specific maintenance tasks are not identified in the Army TM's. Skill level should be identified in terms of Military Occupation Specialty (MOS) in combination with pay grade and experience. Assignment of inadequately skilled maintenance personnel to perform maintenance is a cause factor for leaking and erroneous removal failure modes.

Periodic Inspections

The various types of preventive maintenance inspections which affect the readiness condition of the helicopter were examined for the following:

1. Frequency and interval criteria
2. Clarity and thoroughness of procedures
3. Material and manpower requirements

The daily, intermediate, and periodic preventive maintenance inspections are intended to be performed at the organizational level and are designed to correct deficiencies before malfunctions occur. These inspection procedures were investigated relative to preventive maintenance on hydraulic servocylinders.

The AH-1G Cobra, UH-1H Iroquois, and the CH-47A Chinook preventive maintenance manuals were used as reference material in the following subsections.

Inspection Intervals

Inspection intervals are established at flight-hour intervals rather than at calendar intervals. While this may not directly affect component performance, the management of this system is difficult due to the uncertainty of predictions concerning the accumulation of flight hours on any particular helicopter. Critical inspections are degraded, and maintenance management is under duress when an unusually large number of aircraft are at an inspection interval at any one time.

1. Inspection Procedures (Daily): Sequence Numbers from the Preventive Maintenance Daily (PMD) Inspection Checklist (TM55-1520-210-PMD) would apply to inspection of hydraulic servocylinders in the control system and are shown in Figure 8.

2. Inspection Procedures (Intermediate): Sequence Numbers from the Preventive Maintenance Intermediate (PMI) Inspection Checklist (TM55-1520-210-PMI) would apply to inspection of hydraulic servocylinders on a 25-flight-hour interval basis and are shown in Figure 9.

DAILY INSPECTION CHECKLIST TM 55-1520-210-PMD

Seq. No.	Freq.	Item and Procedure
		CENTER FUSELAGE AREA
		CRITICAL INSPECTION ITEM
3.4		CONTROL LINKAGE AND HYDRAULIC CYLINDERS IN FUSELAGE BELOW PYLON FOR SECURITY, DAMAGE, AND EVIDENCE OF LEAKS FROM CYLINDERS AND CONNECTING LINES. CAREFULLY INSPECT (BY A FEEL TEST) THE RETAINER (P/N 100621 OR P/N 100621-1) FOR LOOSENESS.
		PYLON AREA
		CRITICAL INSPECTION ITEM
4.1		MAIN ROTOR PILLOW BLOCK AND GRIP RESERVOIRS FOR OIL LEVEL, LEAKAGE AND CONTAMINATION' HUB ASSEMBLY, BLADE GRIPS, PITCH HORNS AND DRAG BRACES FOR VISIBLE DAMAGE AND SECURITY. BLADES FOR VISIBLE DAMAGE AND SECURITY.
		CRITICAL INSPECTION ITEM
4.5		SWASHPLATE, SCISSORS AND SLEEVE, AND CONNECTING LINKAGE FOR SECURITY AND VISIBLE DAMAGE. VISUALLY INSPECT CONTROL LUGS (3 EA.) ON SWASHPLATE INNER RING FOR CRACKS. VISUAL INSPECTION IS ALSO REQUIRED ON SWASHPLATE WITH LOAD TRANSFER DEVICES INSTALLED; PLATES DO NOT HAVE TO BE REMOVED TO PERFORM THIS INSPECTION.

Figure 8. Daily Inspection Checklist.

INTERMEDIATE INSPECTION CHECKLIST TM 55-1520-210-PMI

Seq. No.	Freq.	Item and Procedure
		CENTER FUSELAGE AREA
		CRITICAL INSPECTION ITEM
3.4		CONTROL LINKAGE AND HYDRAULIC CYLINDERS IN FUSELAGE BELOW PYLON FOR SECURITY, DAMAGE, AND EVIDENCE OF LEAKS FROM CYLINDERS AND CONNECTING
		PYLON AREA
		CRITICAL INSPECTION ITEM
4.1		MAIN ROTOR PILLOW BLOCK AND GRIP RESERVOIRS FOR OIL LEVEL, LEAKAGE AND CONTAMINATION. HUB, BLADE GRIPS, PITCH HORNS, AND DRAG BRACES FOR VISIBLE DAMAGE AND SECURITY. BLADES FOR SCRATCHES, NICKS, DENTS, EROSION OF LEADING EDGE, AND EVIDENCE OF BOND FAILURES.
		CRITICAL INSPECTION ITEM
4.5		SWASHPLATE, SCISSORS AND SLEEVE, AND CONNECTING LINKAGE FOR SECURITY AND VISIBLE DAMAGE. VISUALLY INSPECT CONTROL LUGS (3 EA.) ON SWASHPLATE INNER RING FOR CRACKS. VISUAL INSPECTION IS ALSO REQUIRED ON SWASHPLATE WITH LOAD TRANSFER DEVICES INSTALLED; PLATES DO NOT HAVE TO BE REMOVED TO PERFORM THIS INSPECTION.
		CRITICAL INSPECTION ITEM
4.7		HYDRAULIC SYSTEM COMPONENTS AND LINES FOR SECURITY, DAMAGE, AND EVIDENCE OF LEAKS. RESERVOIR FOR FLUID LEVEL AND PRESENCE OF CONTAMINANTS. FILLER CAP SEDIMENT SCREEN AND VENT SCREEN FOR CLEANLINESS. WIPE CLEAN ALL EXPOSED PISTON RODS. HYDRAULIC FILTER FOR APPEARANCE OF RED INDICATOR BUTTON.

Figure 9. Intermediate Inspection Checklist.

3. Inspection Procedures (Periodic): Sequence Numbers from the Preventive Maintenance Periodic (PMP) Inspection Checklist (TM55-1520-210-PMP) present an example of the 100-flight-hour interval inspection procedures followed by the U.S. Army for hydraulic servocylinders. This procedure is shown in Figure 10.

A review of these procedures reveals that the U.S. Army does not adequately define many specific details and inspections that are considered mandatory for effective maintenance. The preventive maintenance inspection checklist does not provide tolerances nor adequate references for these tolerances. These checklists should either provide tolerances or adequate references to other applicable U.S. Army documents such as the helicopter TM. Additionally, only general reference is made to the hydraulic servocylinders and not to a specific check that must be accomplished. This general reference can only lead to important areas not being inspected by the already overburdened crew chief.

Maintenance Verification

A mechanic or technician should not inspect his own work--especially in critical systems that involve safety of flight. Maintenance verification is the most glaring omission, and is a major contributing cause of poor maintenance of hydraulic servocylinders.

None of the Army helicopter organizational or depot maintenance level technical manuals specify, or even allude to, maintenance verification checks. TM38-750 indirectly imposes such maintenance verification checks for maintenance on items that directly affect the flight safety of the helicopter. These maintenance verification checks should be clearly delineated in the helicopter TM; the absence of this required check is an indication of the inadequacy of MIL-M-63026(TM).

MIL-M-63026(TM) is the military specification for the presentation of U.S. Army technical manuals. A review of this military specification revealed that no direct requirement for maintenance verification checks was imposed during preparation of the TM's.

Preventive Maintenance Conclusions

The following patterns become apparent when examining the Army preventive maintenance procedures:

1. Theoretically, the "best birds" cycle in and out of preventive maintenance inspections more often than the "worst birds".

PERIODIC INSPECTION CHECKLIST TM 55-1520-210-PMP

Seq. No.	Freq.	Item and Procedure
		CENTER FUSELAGE AREA
		CRITICAL INSPECTION ITEM
3.4		CONTROL LINKAGE AND HYDRAULIC CYLINDERS IN FUSELAGE BELOW PYLON FOR SECURITY, DAMAGE, AND EVIDENCE OF LEAKS FROM CYLINDERS AND CONNECTING LINES. CHECK CYCLIC AND COLLECTIVE CYLINDERS FOR PROPER CLEARANCE BETWEEN SERVO VALVE AND INPUT LEVER ADJUSTING SCREW. CHECK CYCLIC AND COLLECTIVE CYLINDERS FOR SECURITY OF THE RETAINER AND TO ASSURE THAT THE TAB WASHER TANGS ARE BENT AND MAKING CONTACT WITH FLATS ON THE RETAINER. CAREFULLY INSPECT (BY A FEEL TEST) THE RETAINER (P/N 100621 OR P/N 100621-1) FOR LOOSENESS.
		PYLON AREA
		CRITICAL INSPECTION ITEM
4.1		MAIN ROTOR PILLOW BLOCK AND GRIP RESERVOIRS FOR OIL LEVEL, LEAKAGE AND CONTAMINATION. HUB, BLADE GRIPS, PITCH HORNS, AND DRAG BRACES FOR VISIBLE DAMAGE AND SECURITY. FLUSH PILLOW BLOCK. BLADES FOR SCRATCHES, NICKS, DENTS, EROSION OF LEADING EDGE, AND EVIDENCE OF BOND FAILURES.

Figure 10. Periodic Inspection Checklist.

	CRITICAL INSPECTION ITEM
4.5	SWASHPLATE, SCISSORS AND SLEEVE, AND CONNECTING LINKAGE FOR SECURITY AND VISIBLE DAMAGE. VISUALLY INSPECT CONTROL LUGS (3 EA.) ON SWASHPLATE INNER RING FOR CRACKS. VISUAL INSPECTION IS ALSO REQUIRED ON SWASHPLATE WITH LOAD TRANSFER DEVICES INSTALLED; PLATES DO NOT HAVE TO BE REMOVED TO PERFORM THIS INSPECTION. CHECK FOR EXCESSIVE PLAY IN BEARINGS AND BUSHINGS AND BETWEEN COLLECTIVE SLEEVE DRIVE PLATE AND MAST.
	CRITICAL INSPECTION ITEM
4.8	HYDRAULIC SYSTEM COMPONENTS AND LINES FOR SECURITY, DAMAGE AND EVIDENCE OF LEAKS. RESERVOIR FOR FLUID LEVEL. RESERVOIR FILLER CAP SEDIMENT SCREEN FOR CONDITION AND CLEANLINESS. TAKE OIL SAMPLE FROM BOTTOM OF THE HYDRAULIC RESERVOIR, IF CONTAMINANTS ARE EVIDENT, FLUSH SYSTEM AND RESERVOIR. WIPE CLEAN ALL EXPOSED HYDRAULIC PISTONS. HYDRAULIC FILTER FOR APPEARANCE OF RED INDICATOR BUTTON.

Figure 10 - Continued.

This produces the peaks and valleys in the scheduled maintenance loads as the frequency of inspection for the "best birds" is accelerated. Chronic problems become more chronic in such a random atmosphere.

The RAMMIT data show that for the UH-1H, approximately 20 percent of hydraulic servocylinder removals are for "no defect" or "nonfailure" modes. This percentage represents 400 premature or maintenance action removals over a 6-year period. Present practice shows a lack of specific procedures to inspect servocylinders while installed, and automatic referral to the organizational maintenance manual procedure which is: remove--inspect--reinstall. Inspection checklists recommend examining the hydraulic system components in a general way for "security, damage, and evidence of leaks", while the next available manual, the organizational manual, discusses the removal of a servo-cylinder. The missing link here is a procedure in the preventive maintenance check which verifies that a servo-cylinder has definitely failed before removal from airframe.

2. The PMP is performed every 100 days, and by implication should go to greatest depth in terms of component inspection. Items related to inspecting hydraulic systems were quoted previously. Critical inspections are not spelled out in writing to the extent that a verification of airworthiness is established.

   a. The mechanic is not required in the PMP to perform specific detailed checks (except in a general way check for evidence of failures).

   b. Organizational manuals must be referred to for some procedures, and these manuals presume failure.

   c. Quality assurance inspection by designated qualified inspectors is not specified, but is shown as a requirement in TAMMS (TM38-750).

Lack of "specifics" in aircraft preventive maintenance procedures places a burden on the supervisor, and is a contributing cause for hydraulic servocylinder leaking failures and/or premature, unnecessary removals.

Shelf-Life Considerations

Review of hydraulic servocylinders and their constituent component documentation revealed a void as to shelf-life requirements. The inherent design of such components as elastomer products encompasses a natural deterioration process after a period of time. This process of natural deterioration can be accelerated or decelerated by the control of the surrounding environmental conditions. Failures attributed to premature seal wearout due to deterioration are minimized by adequate packing of the components. This packing will minimize the natural deterioration process caused by environmental conditions.

Failure Criteria and Detection

The criteria for establishing system friction limits or allowable leakage are inadequate. The friction test TM55-1520-220-20, Chapter 6, for the collective pitch control hydraulic cylinder states that "A friction drag of approximately 25 pounds is considered normal for the cylinder assembly"; however, the discussion is completely void of allowable tolerances and method for accomplishing the friction test. Also, the system operational check criteria require the mechanic to observe all hydraulic components and connections for evidence of leaks while the system is being operated; but the procedure fails to discuss the allowable leakage tolerances. Consequently, the procedures for trouble-shooting a system that is malfunctioning are so minimal as to be useless except to the most skilled personnel.

Those procedures and criteria that are provided appear to require a flight control system engineer to find problems other than the most obvious, i.e., hydraulic fluid gushing from a cylinder.

Maintenance Skills and Training

Lesson plans for the AH-1G helicopter hydraulic and flight control systems were reviewed. In oder to look at an area that considers the man in the maintenance loop, maintenance personnel in the field were interviewed to assess the training program. The courses were conducted at the U.S. Army Transportation School, Fort Eustis, Virginia.

The lesson plans read well, and attempts are made to keep them updated. An interview with an instructor indicates that the course should be lengthened as a major item of improvement. This same instructor commented that many of the helicopter crew chiefs in the field were inattentive to dirt problems which contributed to the high failure rate problem in hydraulic cylinders.

A weak point in the courses as taught, according to the class instructor, is lack of preventive maintenance instruction in inspection procedures, especially in the Direct Support/General Support hydraulic system courses. This comment points to a high portion of the operational failure rate resulting from component repair. When preventive maintenance techniques and procedures are inadequately taught in formal technical schools, the natural trend is for new maintenance personnel to learn these techniques from maintenance personnel performing like or similar tasks. The problem manifests itself in that these new maintenance personnel learn many of the bad or ineffective techniques and procedures employed by other maintenance personnel. The natural result of ineffective preventive maintenance techniques is accumulation of contamination on piston rod surfaces causing excessive wear of servocylinder components.

Maintenance personnel with an MOS prefix of 67xxx are helicopter/aircraft general repairman and receive formal training on the various helicopter systems. These courses are referred to as "67" series courses. Those personnel with an MOS prefix of 68xxx are helicopter systems specialists for hydraulic (68Hxx), electrical (68Fxx), etc., and receive formal training in their specialty. These courses are referred to as "68" series courses.

The following comments are applicable to a sample lesson plan, "AH-1G Hydraulic Systems":

1. There is no reference to quality assurance.

2. Hydraulic system precaution discussion contains the following negative type statement, "TM55-1520-221-20 does not give specific torque values for the various hydraulic fittings, but care must be taken to insure that fittings are tight enough, but not too tight."

3. Emphasis is exclusively devoted to "knowing the systems." Most probable failure modes and mistakes most often made are not alluded to.

4. The "whys" of good maintenance practice are not sufficiently emphasized relative to hydraulic component preventive maintenance; i.e., the importance of maintaining the cleanliness of moving parts on a day-to-day basis.

With regard to acquired skills, another instructor indicated that On-the-Job Training (OJT) was heavily relied upon to qualify personnel for the rating of Crew Chief. Formal training is not offered subsequent to the initial "67" series class in "AH-1G hydraulics". The "67" and "68" series graduates are not trained well enough to attack the problem of servocylinder leaking and unnecessary failure modes.

Special Tool Requirements

Organizational maintenance manual TM55-1520-210-20P-2 contains a list of airframe tools, ground support and flyaway items for each type of helicopter to be maintained. The tool requirements are not always prescribed in the maintenance procedures, but the listing is adequate and pertinent to each model helicopter. Field interviews indicate that tool availability does not contribute to hydraulic or control system failures.

Component Accessibility

Access panels are not identified in the preventive maintenance cards or in the organizational maintenance manual. Omission of panel identity is not viewed as a cause of hydraulic servocylinder failures per se.

The time required to remove and reinstall access panels to perform preventive maintenance is a leaking mode cause factor in that certain preventive maintenance actions may not be performed, i.e., inspection, cleanliness, adjustments, and lubrication, at assigned intervals if removal is lengthy or difficult.

Degree of Compliance With the Maintenance Procedures and Practices

Maintenance Manuals

Technical manuals for the UH-1 series, AH-1G, OH-6A, CH-47A/B and CH-54 helicopters were reviewed during this analysis. These manuals included the following:

1. Preventive Maintenance Checklists (PMD, PMI, PMP)
2. Organizational Maintenance Manual (-20)
3. Direct Support and General Support Maintenance Manual (-34/-35)

The manuals appear to have been prepared in accordance with MIL-M-63026 (TM). The requirements of this specification are not stringent enough to provide the maintenance personnel with an ordered set of criteria to perform scheduled and unscheduled maintenance actions. This situation contributes to the high early servocylinder leaking failure rate.

Periodic (Preventive Maintenance) Inspection

Periodic inspections are being performed at the various required intervals as defined in the PMD, PMI, and PMP. The requirements of these PMD, PMI, and PMP preventive maintenance checklists are not in sufficient depth to meet the intent of normal preventive maintenance programs. The consequences of non-comprehensive preventive maintenance checklists are increased failures caused by unattached equipment.

Shelf Life Consideration

There is no reference in MIL-C-5503C, MIL-G-5514 or other seal/packing gland specifications pertaining to shelf-life considerations. Shelf-life considerations are as important for equipment such as hydraulic servocylinders that use elastomer components as the shelf-life consideration for the elastomer component itself.

Failure Criteria and Detection

The TM's for the UH-1, AH-1G, OH-6A, CH-47 A/B, and CH-54 helicopters studied did not establish detailed failure criteria and detection procedures that are adequate for the average crew chief to troubleshoot a hydraulic system.

Maintenance Personnel, Skill Levels, Qualifications, and Training

These parameters are identifiable and are complied with at all levels to the extent that they are imposed. The inadequacy of this area is that the requirements are not stringent enough. The U.S. Army maintenance personnel are inadequately trained for the required skills to maintain the complex hydraulic systems on Army helicopters.

Special Tool Requirements

The special tools required to perform maintenance on hydraulic systems and servocylinders are adequately presented in the repair parts and special tools list manuals. To insure that maintenance personnel use the correct tool, these tools should be listed in the applicable section of the organizational maintenance manual.

Component Accessibility

Access to components, while provided by the design of the helicopter, is restricted by at least two inadequacies. The most important is that the maintenance manuals procedures do not identify the access to the components such as hydraulic servocylinders. The other inadequacy is that access panels that must be removed for various scheduled and unscheduled maintenance tasks are difficult to remove and reinstall due to the method of fastening these access doors.

TEST REQUIREMENTS AND PROCEDURES

Hydraulic servocylinders for use with U.S. Army helicopters should be tested to evaluate the inherent design performance characteristics with respect to the projected mission operational environment. The following testing requirements and procedures were investigated:

1. Environmental test and procedures
2. System compatibility testing requirements and procedures

3. Qualification test requirements and procedures

4. Flight test plan and procedures

5. Service test plan and procedures

6. Acceptance test procedures and results

7. Degree of compliance with the testing requirements

This study failed to reveal detailed tests being performed per test plans or requirements by the manufacturers and/or suppliers of hydraulic servocylinders. It is assumed that some tests were performed, but the adequacy of the fulfillment of requirements could not be verified. Recommendations to attain the necessary design verification for future procurements are presented in the Revisions section of this report. Testing itself will not minimize or eliminate failure modes or causes. These tests only point out the existence of the failure mode and its associated cause. The failure modes can be overcome if corrective action is taken prior to production of the servocylinder and/or helicopter.

Environmental Test and Procedures

Environmental testing procedures are essential to predict adequately the performance characteristics of hydraulic servocylinders in the intended environment. Procedures for environmental testing are covered by MIL-STD-810, but the document is not applied to hydraulic servocylinders for Army helicopters.

The benefit that would be gained by the U.S. Army using environmental testing is that unscheduled maintenance for excessive wear of sealing surfaces induced by contamination of these surfaces will be detected prior to the production phase. Engineering changes and/or preventive maintenance provisions can be instituted to minimize these unscheduled maintenance actions, resulting in increased helicopter availability.

System Compatibility Testing Requirements and Procedures

System compatibility testing is an essential procedure because it establishes that the hydraulic servocylinders within the flight control system are compatible with other flight control and hydraulic systems components from a total system standpoint. These tests are required by the procurement and design specifications for simulation of and/or testing of the end item helicopter as well as the component specifications.

Qualification Test Requirements and Procedures

No documentation was found either from vendors or the Army describing qualification testing of hydraulic servocylinders used on Army helicopters. Qualification tests, when completed, are one-time tests unless components are modified or operational requirements are changed.

The qualification testing of the hydraulic servocylinder and its components such as seals and rod end scrapers must be imposed prior to full-scale production. This testing period is the time to determine if the hydraulic servocylinder is of appropriate inherent design for its intended operational environment. For this purpose, the test objective is to simulate conditions more severe than actual Army operational conditions of high vibration and cyclic rates. This should quickly cause leaks around the piston seals of an inadequate design.

Flight Test Plan and Procedures

Flight testing covers activities both by the airframe manufacturer and by the Army for acceptance of new helicopters and for helicopters on which extensive modifications have been made. Because of the proprietary nature of such flight testing procedures and practices, documentation was not released by the airframe manufacturers. It is assumed that these flight tests are conducted in accordance with a procedure approved by the Army procurement office responsible for that helicopter. MIL-H-5440 requires the manufacturer to supply the procuring agency with a detailed functional test specification. The following military specifications require such flight test plans:

1. MIL-F-9490C (USAF), General Specification for Design, Installation and Test of Flight Control Systems, Piloted Aircraft

2. MIL-F-18372(Aer), General Specifications for Design, Installation and Test of Flight Control Systems

3. MIL-T-5522C, General Test Procedure for Aircraft Hydraulic and Pneumatic Systems

These tests must be witnessed by Government personnel. MIL-F-9490C and MIL-F-18372 are not specifically imposed by the military specification upon the airframe manufacturer. The manufacturers' flight test categories are as follows:

1. Developmental Flight Tests-Developmental flight tests of a component or system shall demonstrate that the helicopter combination is performing within the specified operational requirements. These tests shall be designed for the flight

control and hydraulic systems to identify and aid in correcting deficiencies in the basic airframe handling qualities. These tests will also be used for flight controls for component and subsystem development.

2. Preproduction Flight Tests-These tests consist of a series of specific tests designed to prove functional suitability, consistency of operation, and the accuracy of performance of the flight controls, hydraulics, and all of their related functions and modes of operation prior to committing the helicopter to full production.

3. Production Flight Tests-Production tests shall consist of the preflight and functional flight checks accomplished on each production installation submitted for acceptance. Production flight tests shall be accomplished in accordance with preflight and flight test procedure prepared by the airframe manufacturer and approved by the procuring activity.

U.S. Army flight tests fall into the following 2 primary categories:

1. Engineering flight test for new helicopters

2. Maintenance operational flight test for helicopters when required by scheduled (preventive maintenance) and unscheduled maintenance

All Army flight testing of aircraft and helicopters is governed by TP AVN 23-16, "Test Flights and Maintenance Operational Checks for Army Aircraft".

Engineering flight tests by U.S. Army personnel are conducted after the contractor has successfully demonstrated that the helicopter has met or exceeded the Army operational requirements. Their tests are designed to insure that the operational performance of such equipment as hydraulic servocylinders will function within the design limits of the helicopter operational environment.

Maintenance operational flight tests by Army personnel are conducted subsequent to all PMI and PMP preventive maintenance checks. These flight tests are also conducted after unscheduled maintenance actions involving maintenance conducted in safety of flight equipment such as servocylinders. Army flight test procedures which impact hydraulic servocylinder performance are shown in Table VI. These procedures are extracted from TM55-1520-220-20, Chapter 3, Section III, "Aircraft Test Flight Inspection Checklist".

These flight test procedures for flight control performance are capable of detecting many existing flight control system failures or impending failures.

TABLE VI. TEST PROCEDURES	
Before Starting Engine	
Pedals	- Freedom of movement through range of travel, neutral.
Starting Engine and Runup	
RPM 6000	- Force trim OFF, check controls for any tendency to creep or motor, freedom. Note Keeping the fingers around the cyclic grip, but not touching it, lightly tap the cyclic in various directions with the fingertips. Movement should stop when pressure is stopped. Each pedal should be checked by tapping lightly with the foot with no pressure on the opposite pedal. The controls should not motor or creep when no pressure is applied. With force trim OFF the controls should operate smoothly (no creeping, binding or chattering) with no feedback or excessive friction, within about 1 inch of controls center.
Force Trim ON	- Check cyclic gradient forces nearly the same in all directions, no play. Recheck in all directions within 1 inch of cyclic center. Note With force trim ON it should take approximately equal force to move the cyclic in all directions while making movements of approximately 1 inch. Force required to move the pedals

TABLE VI - Continued

	should be about the same for either pedal. Using the cyclic release button, position the cyclic and pedals in various positions, within about 1 inch of neutral. The controls should hold the selected positions, and the spring force should be the same in all directions.
Collective Pitch Lever	- Adjustable friction completely free. Check built in friction is: 8 pounds minimum, 12 pounds maximum.
	Note
	Move the collective up to about mid-travel and then back down. The force required to move the collective should be 8-12 pounds and be about the same in each direction. It is recommended that a fish scale be used to make this check with greater accuracy. However, the correct effort to lift the collective is about the same as that required to lift a loaded M-1 rifle. Friction may be noticeably less on abnormally damp days. Friction adjusted on damp days may be too heavy on dry days.
Collective Pitch Lever	- Minimum check—adjustable friction will adequately increase friction, set friction OFF.
Hover Checks	
Cyclic	- Move various directions. Note tip path plane for proper movement.
Tail Rotor Pedals	- Depress each slightly; feel that aircraft tries to turn in proper direction.

TABLE VI - Continued

Collective Pitch	- Increase smoothly, noting that the CG feels normal until at 3-5 foot hover.
Control Position	- Stabilized hover. Cyclic should be nearly centered, pedal position normal. Note vibrations, Any excessive control displacement should be sufficient warning to require rigging check. Consider wind influences.
Control Response	- Check with small inputs; note any lack of response or binding. Lack of proper response or binding is cause to terminate flight and determine cause.
Power Cylinder Check	- Move cyclic smoothly 6 to 8 inches along a 45 degree line from left rear to right forward several times (at a rate of about 2 to 3 seconds per move.) No restrictions to movement should be felt. Check similarly from right rear to left forward. Check by turning off one HYD SYS at a time. Note Total cyclic movement should be about 6 to 8 inches at rate of about 2 or 3 seconds per movement. If too rapid, it is possible to cause the same reaction that would occur with a hydraulics failure. One hand, or the observer's hand, should be kept on the hydraulic control switch to immediately turn hydraulics off and then on again if necessary. You are checking that the hydraulic boost system will function properly in flight if moved at a rate more rapid than normal.
Turns	- Make hovering turns in both directions to check tail rotor response and rigging.

TABLE VI - Continued	
Sideward Flight	- Fly in both directions to check cyclic response and rigging.
Flight	- Do backward and forward flight into a 15-knot wind to check cyclic response and rigging.
Takeoff and Climb	
Normal Takeoff	- Climb at 60-70 knots. Note control positions normal.
Autorotation	- Note vibrations. Note that sufficient right pedal remains.
Hydraulic Control Switch OFF	- Caution light ON. Check that helicopter is easily controllable; no excessive forces to right front quandrant; cyclic and pedal forces. Collective should go down and up in pressure without excessive force. There should be no excessive feedback in the controls.
Engine Topping Out	
Concurrent Vibration Test	- Check control positions and forces. Note that sufficient left pedal remains. Note vibration level.
Control Rigging Check	
Airspeed Test	- Needle and ball centered. Note that cyclic control is nearly centered, force trim holds controls in position. Right pedal should be slightly forward. Investigate rotor vibrations. Aircraft should fly smoothly through entire speed range.

TABLE VI - Continued	
Airspeed to Hover	- Accomplish a zero-airspeed 1500-foot altitude hover. Note any 1-per-revolution vibration.
Stabilized Airspeed	- 70 knots. Note vibration level. Descend with low pressure and note increased vibrations.
Level Off and Accelerate	- Increase airspeed from 70 knots to VNE unless vibrations become severe. Note any 1-per-revolution vibrations and airspeed at which they became evident.
After Landing Check	
Controls	- Collective pitch full down, cyclic centered, pedals neutral.

Service Test Plan and Procedures

The purpose of these service tests is to assist the maintenance personnel in checking the operation of the helicopter and such essential equipment as hydraulic servocylinders under service conditions. These tests are usually performed at U. S. Army installations on production model helicopters during which time Army maintenance and flight personnel perform typical operational tasks. This type of testing provides the U.S. Army with reasonable assurance that the item being tested will perform the required tasks, provide the desired helicopter availability, and identify problem areas. The procedures for conducting these tests for maintenance-related areas are delineated in MIL-STD-471, "Maintainability Demonstration Testing". Whenever problems are encountered during these service tests, engineering change proposals are generated to modify the defective equipment and/or procedure. The military specifications for hydraulic servocylinders do not call out MIL-STD-471 as part of their tests.

Acceptance Test Procedures and Results

Acceptance test procedures and plans are an essential element of all procurement activities. These tests include operational test of the item being procured, whether it is the whole helicopter or a hydraulic servocylinder. The acceptance test of hydraulic servocylinders should be covered by the following military specifications:

1. MIL-H-8775C
2. MIL-H-5440F
3. MIL-T-5522
4. MIL-C-5503C

These military specifications elude to various classes of QA and other tests, none of which delineate acceptance criteria.

MIL-T-5522 does require that the contractor prepare and submit to the procuring agency a detailed test procedure at least 30 days prior to such test. This test plan is submitted for information and comment by the procuring agency. This does not imply that the procuring agency will be able to disapprove such test procedures nor assure that their valid comments will be incorporated. Of course, acceptance tests do not guarantee the helicopter to be free from impending failures. However, a good acceptance test affords an opportunity to determine all existing defects and to note symptoms of some impending failures so that the manufacturer must repair the helicopter before receiving full payment. At this point, defective hydraulic servocylinders are the issue, not servocylinders with inherently poor design.

Degree of Compliance With the Test Procedures and Requirements

This study failed to reveal detailed tests being performed per test plans or requirements by the manufacturers and/or suppliers of hydraulic servocylinders. Each airframe manufacturer and subcontractor allege that these tests have taken place, yet supportive data are not available. It is assumed that some tests were performed, but the adequacy of the fulfillment of requirements could not be verified. The degree to which tests should be required could not be readily ascertained.

REVISIONS AND SOLUTIONS

REVISIONS

The revisions to the various documents that are used to control or verify the adequacy of hydraulic servocylinders operating in the U.S. Army helicopter environment are presented in this section. These revisions are intended to reduce or eliminate the causes of many of the failure modes specifically addressed in the previous sections of this report. All identifiable costs associated with particular types of revisions are presented within the cost section of this document.

Design Requirements

Specification Control Documentation

Specification control documents such as drawings should include the specific requirements to which the hydraulic servocylinder must operate. These will ensure that the Army's requirements are adequately improved during design and subsequent manufacture. The requirements that must be considered as a minimum are as follows:

1. Incorporation of applicable documents

a.	ABC-STD-50	Surface Texture (Formerly MIL-STD-10, Surface Roughness)
b.	FED-STD-1	Standard for Laboratory Atmospheric Conditions for Testing
c.	MIL-STD-100A	Engineering Drawing Practices
d.	MIL-STD-480	Configuration Control
e.	MIL-STD-810B	Environmental Testing
f.	MIL-C-5503C	General Requirements for Aeronautical Hydraulic Actuating Cylinders
g.	MIL-G-5514F	General Requirements for Gland Design; Packings Hydraulic

h. MIL-E-5272 — General Specification for Environmental Testing, Aeronautical and Associated Equipment

i. MIL-S-5049 — Hydraulic Piston Rod Scrapers

j. MIL-T-5522C — General Test Procedure for Aircraft Hydraulic and Pneumatic Systems

k. USAS-114,5, Y14.5 1966 — Dimensioning and Tolerances for Engineering (Formerly MIL-STD-8)

2. U.S. Army operational environments (no specific reference to these requirements could be found in servocylinder specifications)

   a. Vibration, shock

   b. Hydraulic system pressure

   c. Cyclic rate

   d. Force pressure

   e. Stroke length

   f. Actuator exposure to environmental factors

      Temperature
      Sand, dust
      Moisture

   g. Mission of helicopter

3. Tolerance requirements

   a. Allowable tolerance buildup

      Sizing
      Pressures

   b. Allowable leakage

4. Reliability and maintainability quantitative and qualitative requirements

a. MTBF

b. MTTR

c. MMH/FH

d. Availability

e. Level of repair

f. Vibratory loads

In addition, the typical operating requirements necessary for helicopter operations should be coordinated with and imposed upon the suppliers of hydraulic servocylinders. Such an operational profile would determine the reliable performance of the flight control system which contains the hydraulic servocylinder actuator. This lack of specific requirements during the design phase results in the premature removals of the equipment for such failure modes as leaking. Most leakage failures are induced by wear of gland seals that involves violations of the environmental constraints described.

Component Selection Criteria

Criteria for selecting components such as gland seals and piston scrapers for the hydraulic servocylinder must consider the following as a minimum:

1. Design life and cost constraint

   a. MTBF

   b. MTTR

   c. Availability

   d. MMH/FH

   e. Cyclic rate

   f. Stroke length

2. Design loads of the system

   a. Pilot input forces

   b. Required output forces

3. Subsystem parameters

   a. Hydraulic system pressure

   b. Hydraulic system capacity

   c. Hydraulic system filtration

4. Operational environment

   a. Vibration

      Nominal
      Gun fire

   b. Weapon system purpose

      Gun ship
      Troops
      Cargo
      Medical/evacuation

   c. Temperature profile

      System
      Ambient

   d. Sand, dust

   e. Moisture

The component selection criteria should then be used to establish a quality assurance program plan. The testing of these components per the applicable military specifications provides the basis for a qualified products list. These qualified products lists can then be the basis for selecting the components for the hydraulic servocylinders. The extensive use of nonqualified components introduces the likelihood that components will not perform their intended function. Components such as piston rod scrapers that do not perform their intended function introduce the possibility of contamination being ingested into the servocylinders. Such contamination will wear out the seals, and leakage will result.

Military Specifications and Standards

General specifications for the procurement of hydraulic servocylinders and their components should include the provisions of

MIL-STD-490, Military Standard Specification Practices. The requirements that should be imposed are as follows:

1. Item description

2. Characteristics

    a. Performance

    b. Physical characteristics

        Weight
        Dimensions
        Transport and storage requirements
        Durability factors
        Health and safety criteria
        Vulnerability

    c. Reliability

    d. Maintainability

    e. Environmental conditions

    f. Transportability

    g. Design and construction

        Materials and processes
        Electromagnetic interference
        Identification and marking
        Workmanship
        Interchangeability

    h. Safety

    i. Human performance

The U.S. Army helicopter operational requirements should be included in the hydraulic servocylinder specifications. Realistic operational environmental requirements should be incorporated into flight control system, hydraulic system, and servocylinder specifications in order to minimize the possibility of anomalies occurring aboard U.S. Army helicopters. These improved specifications would reduce the number of premature failures that are being experienced with the presently used hydraulic servocylinder designs.

An example of the inadequacy of current military specifications to cope with the actual operational requirements of the U.S. Army is MIL-S-5049B. This specification controls the design of piston rod scrapers; the current inventory scrapers do not exclude the very minute yet abrasive Vietnam coral dust.

Contract Specifications

Contract procurement specifications should be prepared for each type of hydraulic servocylinder. These specifications may be prepared by either the U.S. Army or its contractor.

These specifications should include the following as a minimum:

1. Specific design requirements
   a. Operating profile
   b. Hydraulic subsystem parameters
   c. Flight control subsystem parameters
2. Environmental requirements
   a. Vibration
   b. Temperature
   c. Sand, dust
   d. Moisture
3. Life-cycle cost constraints
   a. MTBF
   b. MTTR
   c. Availability
   d. MMH/FH
   e. Cyclic rate
   f. Stroke length
   g. Level of repair

When realistic requirements in the contract specifications are imposed on the contractor, the likelihood of failure modes such as leakage occurring is minimized. Servocylinder hydraulic leaks are usually the result of inadequate parameters being supplied to the designer.

Design Requirements To Eliminate Induced Failures

An FMEA should be accomplished for each preliminary design to reveal the failure modes, causes, effects and design compensating provisions.

In determining the failure modes, attention should be given to the following performance parameters:

1. Vibration, shock
2. Hydraulic system pressure
3. Cyclic rate
4. Force pressure
5. Stroke length
6. Actuator exposure to environmental factors
   a. Temperature profile
   b. Sand, dust
   c. Moisture
7. Mission of helicopter
8. Component materials
9. State of the art

Quality Assurance

A comprehensive QA Program Plan must be established and imposed upon the contractor and his vendors for each helicopter and its essential components such as hydraulic servocylinders. To be effective as a management tool, the QA program must consider the following areas as a minimum.

Vendor Quality Control

Each vendor must establish a comprehensive QA program at his respective facility. This program should include, as a minimum:

1. Verification that dimensional tolerances are adhered to
2. Verification of material integrity
3. Functional tests, if applicable
4. Lot sampling plans used
5. Proof that packing and shipping are accomplished in accordance with the applicable military specifications

The failure modes most likely to occur as the result of inadequate vendor QA procedures are leakage due to damaged gland seals or scrapers, longitudinal scratches on the piston or barrel surfaces, and surface finishes out of tolerance so that an effective seal cannot be maintained. Also, improper packaging that allows the piston rod surfaces to be exposed could cause damage to piston surfaces, causing leakage past the gland seals.

Airframe Manufacturer Receiving Inspection

Receiving inspections at the manufacturer's facility should include as a minimum:

1. A visual inspection to determine if any obvious damage was experienced during shipping.
2. Operational checks of hydraulic servocylinders. These should be accomplished in accordance with the sampling techniques established by MIL-STD-105D and MIL-C-5503C.

The adequacy of source inspections by the vendor's QA personnel and the packaging and shipping techniques have a direct effect on the frequency of operational checks required by MIL-STD-105D. That is, the frequency of subsequent checks is a function of quality of the operational checks previously performed.

The failure mode that could be reduced or eliminated is binding, where damage during transit has caused the actuator to be bent or jammed. This type of damage usually results from improper packing for shipment from vendor to airframe manufacturer.

Therefore, whenever improper packaging is noted, a reviewing operational inspection should be required prior to installation in the helicopter.

Initial Installation Procedures

Critical or safety of flight equipment such as hydraulic servo-cylinders should receive QA inspections during and immediately after the installation process.

1. An installation check should be performed and include as a minimum:

   a. Verification that installation procedures are in possession of mechanics.

   b. Verification that installation procedures are followed by mechanics.

   c. Verification that no physical defects are observed.

   d. Verification that applied torque values are within tolerances.

   e. Verification that safety wire or other positive locking provision requirements are accomplished in accordance with applicable military specification.

2. The preoperational QA inspection should be performed and include as a minimum verification of the following:

   a. Servocylinders are properly installed.

      Torque values are within tolerance.
      No physical defects exist.
      The installation sheet is signed off.
      Safety wiring is in accordance with the applicable specification.

   b. No hydraulic leakage occurs.

   c. No obstructions exist.

   d. All mechanical, hydraulic and electrical interfaces are complete.

The failure mode that would be minimized or eliminated would be that of connecting rods becoming disconnected from the servocylinder in flight. The occurrence of such a failure would likely result in a loss of flight controls and subsequent crash damage to the helicopter. The initial installation inspections would minimize failure modes induced by installation errors.

Functional Test Procedures

Functional tests of hydraulic servocylinders which will be witnessed by QA or other authorized personnel should include as a minimum verification of the following:

1. Allowable leakage rates are not exceeded.

2. Breakaway forces are not exceeded with hydraulic boost applied.

3. Functional flight tests are performed which show that no operational restrictions are encountered which are the result of the hydraulic servocylinder.

The type of QA inspection will reveal such failure modes as air in the system, leakage around gland seals, and excessive friction between gland seals and piston/barrel surfaces.

Mandatory Inspection Points

Hydraulic servocylinders for flight control systems have certain inspection criteria that should be clearly enumerated on QA inspection sheets. These QA mandatory inspection point checklists must be accomplished at airframe manufacturer, hydraulic servocylinder vendor, component supplier and U.S. Army maintenance facilities by QA or maintenance verification personnel.

The mandatory inspection point checklist for hydraulic servocylinders installed in the helicopter should include as a minimum:

1. Mechanical links

    a. Input links

        Securely fastened
        Not binding

b. Output links

Securely fastened
Not binding

c. Airframe attach points

Securely fastened
No evidence of cracks

2. Hydraulic

a. Input/return ports

No evidence of leaks
Input/return lines not reversed

b. Piston seals

Leakage rate does not exceed specifi[illegible] requirements (example, 1 drop in 2[illegible])

3. Electrical (if applicable)

a. Connectors properly connected

b. Wiring not frayed

4. Safety wiring in accordance with accepted practices

Component Sampling

Hydraulic servocylinders and their constituent components such as gland seals and piston scrapers are very amenable to lot sampling techniques. The frequency of these inspections is governed by MIL-STD-105D. There are basically 2 categories of tests that should be imposed upon servocylinder components.

1. Lot or batch testing/inspection requirements for components such as gland seals should be performed and should include:

a. Material ingredients

b. Process procedures

c. Process equipment

Tolerances
Inspections
Calibrations

d. Component sizing/tolerances

e. Elastomer product

Elasticity
Bonding

f. Reference to applicable documents

Military specifications
Military standards
Contract specifications
Vendor QA procedures

2. Lot sampling requirements for hydraulic servocylinder components such as pistons or barrels should be performed and include:

a. Material hardness

b. Surface finish

c. Dimensional sizing

Maintenance Procedures and Practices

Maintenance Manuals

These recommended revisions in technical and preventive maintenance manuals, if adopted, will eventually affect all aircraft in the U.S. Army inventory. For purposes of this report, manuals for the UH-1D/H are referred to as representative baselines for candidate improvements.

The manuals reviewed which govern UH-1D/H helicopter maintenance were:

1. TM55-1520-210-20PMD, Preventive Daily

2. TM55-1520-210-20PMI, Preventive Intermediate

3. TM55-1520-210-20PMP, Preventive Periodic

4. TM55-1520-210-20, Organizational Manual

5. TM55-1520-210-20P-1, -2, -3, Organizational Maintenance Repair Parts and Special Tools List

The technical organizational and direct/general support maintenance manuals are essentially complete with respect to maintenance procedures. The following recommendations are made in order to make the manuals more comprehensive and to improve the quality verification of aircraft maintenance:

1. Functional descriptions of each system should begin each chapter. This would assist in understanding the operation of the system and the required troubleshooting procedures. An example of functional description of a hydraulic servocylinder can best be shown by a comparison between an Army TM and its equivalent Navy manual.

   Example from Army manual:

   TM 55-1520-210-20

   6-11. Overhaul – Tail Rotor Control Hydraulic Cylinder. Part No. 1660. (Refer to TM 55-1650-312-40).

   6-12. Overhaul and Test – Flight Control Servo Cylinders – P/N's 105875, 100575, 100585-1, 100525-7, and 100600-4.

   (Refer to TM 55-1650-294-40.)

   Example from Navy manual:

   NAVAIR 01-110HCA-2-1

   6-3. SERVO CYLINDERS.

   6-4. DESCRIPTION. Hydraulic servo cylinders are installed in the flight control systems to relieve pilot effort required for control and to prevent rotor feed-back being transmitted to the controls.

The anti-torque cylinder consists of a servo unit and actuating cylinder. The cyclic and collective cylinders consist of an irreversible valve, servo unit and actuating cylinder.

6-5. REPAIR - SERVO CYLINDERS. Refer to the following publications for cylinder repair.

PUBLICATION NO.	BELL PART NO.	VENDOR PART NO.
TM 55-1650-294-40	204-076-052-7	105875 and 100585-7
TM 55-1650-322-40	204-076-003-1	100310
TM 55-1650-312-40	204-076-053	1660 series
TM 55-1650-334-40	204-076-053	SGT 220-1 and CSC 546-2

2. Materials and manpower requirements should be provided for each maintenance procedure. An example of Navy intermediate maintenance manuals which includes materials and manpower requirements is:

NAVAIR 01-110HCA-2-1 **SECTION VI**
Paragraph 6-1 to 6-7

Tools and Equipment Required

None required.

Material Required

Hydraulic Fluid	MIL-H-5606
Packing	AN6227-11

Manpower Required

One man required

Quality Assurance Required

Inspection required when step is underlined.

3. Maintenance verification provisions need to be incorporated in the maintenance procedures at all levels of maintenance in order to certify the following:

   a. Proper material condition

   b. Correct component assembly or installation

   c. Proper system functioning following overhaul or repair

Incorporation of maintenance verification into all manuals will have a major impact on reducing hydraulic servocylinder leaking and unnecessary removal failure modes.

<u>Periodic Inspections</u>

This investigation has uncovered certain weaknesses in the daily, intermediate, and periodic preventive maintenance cards. Samples of NAVAIR publications are included as representative examples of the recommended course of action to be followed.

1. Daily Preventive Maintenance: Figure 11 is an example of a maintenance requirements card. The details of inspection to be performed are delineated, including access panel identity. Other requirements shown are manpower, time to perform, test equipment, and material condition. Warning and caution notes are included when necessary.

CARD 3	TIME 00:04	RTG. NO. PC 1	POST FLIGHT		ELEC PWR N/A HYD PWR N/A
TASK MIN.	**WORK AREA**	**MOS. NO.** PC 1	**PUBLICATION NUMBER** NAVAIR 01-230HLC-6-2	**CARD SET DATE** 1 November 1968	**CHANGE NO.**
1.0	5	**1.** RH main gearbox: a. open transmission service platform 86 (SH-3D, 83). b. primary and utility manifold red warning buttons for extended position (indicates possible system contamination). c. primary servo cylinders for evidence of leakage. d. fire bottle for proper pressure.			
0.3	5	**2.** RH rotary wing head: a. blade inspection method pressure indicators for black indication; blade indicator covers for cracks and internal moisture. b. visible portions of main rotor blades for obvious damage. c. rotor head for evidence of leakage. d. lubricating oil reservoir for FULL indication (SH-3D only). e. utility reservoir for FULL indication.			
0.5	4	**3.** RH engine: a. open engine sevice platform 89 (SH-3D, 86). b. close transmission service platform 86 (SH-3D, 83). c. remove oil tank cap; check oil level and reinstall cap.			

Figure 11. Example of Navy Maintenance Requirements Card.

The Army should adopt a similar card system that describes specific actions in the daily preventive inspection process.

2. Intermediate and Periodic Preventive Maintenance: These levels of scheduled maintenance are approximately equal to the Navy organizational calendar maintenance check. The main difference is in the interval. The Army uses flight hour, and the Navy uses calendar intervals. Figure 12, NAVAIR 01-110HCA-6-4, is a typical example of a scheduled maintenance inspection action involving a hydraulic servocylinder in the flight control system. Each subsequent item inspected describes what actions are taken. Manpower, skill level, materials and special tools are delineated. Quality assurance is specified as an integral part of the process. Special notes are provided as well as warnings and caution when required.

   The following three areas regarding scheduled maintenance at the organizational level should be incorporated into the U.S. Army maintenance documentation:

   a. Present detailed steps which must be accomplished for inspection.

   b. Adopt an interval of scheduled maintenance which incorporates a planned preventive maintenance schedule based on calendar time versus airframe time. (Note: Maintenance for some components will still be required at certain accumulative operating hours under this system.)

   c. Integrate maintenance verification into the inspection procedure as a requirement--in writing. This maintenance inspection sign-off certifies that procedures, as specified, have been performed correctly.

Shelf-Life Considerations

Shelf-life time limits should be established for hydraulic servocylinders and elastomer components. The effect of the following factors must be considered when establishing a shelf life:

1. Material ingredients
2. Environment
3. Packaging of components

CARD 42	TIME 01:00	RTG. NO.	AMH 1	CALENDAR	HYDRAULIC CYLINDER UNIBALL	ELEC PWR N/A HYD PWR OFF
TASK MIN.	WORK AREA	MOS. NO.	6055 1	PUBLICATION NUMBER NAVAIR 01-110HCA-6-4	CARD SET DATE 15 February 1970	CHANGED

Assisted by AMS-3 (60.0 Min.)

SPECIAL TOOLS/EQUIPMENT

Scales, Spring (0-5 lb.)
Wrench, Torque (100-750 in. lb.)

CONSUMABLES/REPLACEMENT PARTS

Cotter Pin (3)	MS24665-151
Cotter Pin	MS24665-152
Lockwire	MS20995C32

TASK MIN.	WORK AREA	
60.0	3, 5	1. Hydraulic Cylinder Support Bearing.

a. Disconnect cyclic hydraulic cylinder extension tube clevis/rod end from swashplate.

b. Remove spring from swashplate bracket.

c. Disconnect collective hydraulic cylinder extension tube clevis/rod end from collective lever assembly.

d. Disconnect tube assemblies from bottom of cyclic and collective hydraulic cylinders.

e. Actuate cylinder to full up position (bottomed).

TASK MIN.	WORK AREA	CARD 42.2	PUBLICATION NUMBER NAVAIR 01-110HCA-6-4	CHANGED	ELEC PWR N/A HYD PWR OFF

f. Move top of each cylinder laterally until bottomed. Attach pound reading spring scale to clevis/rod end and note reading to move cylinder through full lateral travel.

NOTE: The required force shall be 1.0-2.5 lb. If the required force is acceptable proceed to step k. If the noted force is not within limits (1.0-2.5) proceed with step g.

NOTE: QA shall witness the following tasks.

g. Check nut for evidence of looseness. If loose, straighten tab and torque nut 200-250 in. lb. and secure nut with tab on lock.

h. Raise boot and remove lockwire from adjustment nut.

i. Torque adjustment nut 400-450 in. lb. and move cylinder assembly through full lateral travel several times to ensure proper seating of bearing surfaces.

j. Loosen adjustment nut and retighten until a force of 1.0-2.5 lb. is required to move cylinder laterally. Lockwire nut and reposition boot.

k. Reconnect cylinder assembly to collective lever assembly. Install cotter pin.

l. Reconnect tube assemblies to bottom of cylinder assemblies and install cotter pins.

End of Card

Figure 12. Periodic Requirements Cards.

Establishing shelf-life time limits and clearly indicating the shelf-life expiration data on the package will minimize the possibility of a component being installed that has exceeded its shelf life. Components that have exceeded their shelf life, such as packing glands, seals, etc., may have started their natural deterioration process.

Failure Criteria and Detection

The criteria for establishing a failed piece of equipment and detecting failures in equipment such as hydraulic servocylinders should include the following:

1. State of the art
2. Allowable manufacturing tolerances
3. Leak criteria by inherent designs
4. Hydraulic system capacity
5. Allowable friction
6. Operational characteristics of the system and servocylinders

Such establishment of failure criteria and detection would reduce the present significant level of "no failure" removal modes. Examples of failed hydraulic servocylinders at the organizational maintenance level are as follows:

1. Leakage around piston seal that exceeds 1 drop in 25 cycles of operation
2. Cylinder drag friction in excess of 25 pounds
3. Longitudinal scratches on exposed piston rod surfaces when piston is fully extended
4. Pitted or scored piston rod surfaces

Similar criteria could be used at other levels of Army maintenance provided the servocylinder is checked under conditions similar to those experienced in the helicopter.

Maintenance Personnel Skill Level, Qualifications, and Training

The following revisions are recommended:

1. Lengthen initial formal training. The "AH-1G Helicopter Repair Course" is currently 11 weeks, 3.5 days in duration. The personnel receive only 40 hours of instruction in the flight control and hydraulic systems. This should be expanded to 120 hours to include a minimum of 40 hours of actual rigging of the flight control system and maintenance practices concerning troubleshooting, removal and replacement of hydraulic servocylinders.

2. Include pointers on good maintenance practices in the lesson plan. An example would be to keep hydraulic servocylinder piston surfaces free from contaminants such as oil, grease, sand, and dirt.

3. Institute follow-on formal training to augment on-the-job training (OJT).

4. Identify skill levels required for performing maintenance.

Overall upgrading of training and skill level requirements provides a major impact on improved hydraulic servocylinder service life.

Component Accessibility

It is recommended that access panels be identified with respect to both scheduled and unscheduled maintenance. Access should be identified in the preventive maintenance and technical manuals. In corresponding Navy technical publications, access panels for the UH-1E are readily identified and numbered 1 through 91; they are referred to in maintenance procedures in terms of removal and installation.

Test Requirements and Procedures

A comprehensive Test Program Plan must be established, and these test requirements must be imposed upon contractors and their vendors for each helicopter design and its major components. To be effective as a management tool, the test program must consider the following areas as a minimum:

1. Environment

2. System compatibility

3. Qualification

4. Flight

5. Service

6. Acceptance

Each of these areas is discussed as to the specific recommendation to eliminate or minimize the current anomalies.

Environmental Testing

Environmental testing of aeronautical equipment is controlled by MIL-STD-810B. The operational parameters of the hydraulic servocylinder, as delineated by the applicable contract specification, should be tested using the test methods of MIL-STD-810B for each category of test. During these tests, the hydraulic servocylinder should be operated in accordance with the requirements set forth in the applicable contract specification. Some of these environmental tests are required by MIL-C-5503C; however, they do not adequately reflect the Army operating environment. Realistic operating environmental parameters must be established in order to effectively test the hydraulic servocylinders per the methods established by MIL-STD-810B.

The environmental characterisitcs that are recommended by MIL-STD-810B, Table I, and that should be considered as a minimum are as follows:

1. Temperature and Pressure

   a. High Temperature. The high temperature test is conducted to determine the resistance of equipment to elevated temperatures that may be encountered during service life either in storage (without protective packaging) or under service conditions. In equipment, high temperature conditions may cause the permanent set of packings and gaskets. Binding of parts may also result in items of complex construction due to differential expansion of dissimilar metals. Rubber, plastic, and plywood may tend to discolor, crack, bulge, check or craze. Closure and sealing strips may partially melt and adhere to contacting parts.

b. Low Temperature. The low temperature test is conducted to determine the effects of low temperature on equipment during storage (without protective packaging) or service use. Differential contraction of metal parts, loss of resiliency of packings and gaskets, and congealing of lubricants are a few of the difficulties associated with low temperatures.

c. Temperature Shock. The temperature shock test is conducted to determine the effects on equipment of sudden changes in temperature of the surrounding atmosphere. Cracking or rupture of materials due to sudden dimensional changes by expansion or contraction are the principal difficulties to be anticipated. These could occur in service due to rapid altitude changes during shipments and airdrops.

d. Altitude. The altitude test is conducted to determine the effects of reduced pressure on equipment. Damaging effects of low pressure include leakage of gases or fluids from gasket-sealed enclosures and rupture of pressurized containers. Under low pressure conditions, low density materials change their physical and chemical properties. Damage due to low pressure may be augmented or accelerated by the contraction, embrittlement, and fluid congealing induced by low temperature. Erratic operation or malfunction of equipment may result from arcing or corona. Greatly decreased efficiency of convection and conduction as heat transfer mechanisms under low pressure conditions is encountered. This test method is for the purpose of determining the ability of equipment to operate satisfactorily during and following exposure to both reduced pressure and temperature conditions encountered during flight.

2. Corrosion and Erosion

a. Rain. The rain test is conducted to determine the effectiveness of protective covers or cases to shield equipment from rain. This test is applicable to equipment which may be exposed to rain under service conditions. Where a requirement exists for determining the effects of rain erosion on radomes, nose cones, etc., a rocket sled test facility or other such facility should be considered. Since any test procedure evolved would be contingent on requirements peculiar to the test item and the facility employed, a standardized test procedure for rain erosion is not included in this test method.

b. Humidity. The humidity test is applicable to all equipment and is conducted to determine the resistance of equipment to the effects of exposure to a warm, highly humid atmosphere such as is encountered in tropical areas. This is an accelerated environmental test, accomplished by the continuous exposure of the equipment to high relative humidity at an elevated temperature. These conditions impose a vapor pressure on the equipment under test which constitutes the major force behind the moisture migration and penetration. Corrosion is one of the principal effects of humidity. Hygroscopic materials are sensitive to moisture and may deteriorate rapidly under humid conditions. Absorption of moisture by many materials results in swelling, which destroys their functional utility and causes loss of physical strength and changes in other important mechanical properties. Insulating materials which absorb moisture may suffer degradation of their electrical and thermal properties.

c. Fungus. The fungus test is used to determine the resistance of equipment to fungi and to determine if such equipment is adversely affected by fungi under conditions favorable for their development, namely high humidity, warm atmosphere, and presence of inorganic salts.

d. Salt Spray. The salt fog test is conducted to determine the resistance of equipment to the effects of a salt atmosphere. Damage to be expected from exposure to salt fog is primarily corrosion of metals, although in some instances salt deposits may result in clogging or binding of moving parts. In order to accelerate this test and thereby reduce testing time, the specified concentration of moisture and salt is greater than is found in service. The test is applicable to any equipment exposed to salt fog conditions in service.

e. Dust. The dust test is used during the development, qualification test, and evaluation of equipment to ascertain its ability to resist the effects of a dry dust (fine sand) laden atmosphere. This test simulates the effect of sharp edged dust (fine sand) particles, up to 150 microns in size, which may penetrate into cracks, crevices, bearings, and joints and cause a variety of damage such as fouling moving parts, making relays inoperative, forming electrically conductive bridges with resulting "shorts" and acting as a nucleus for the collection of water vapor (hence, a source of possible corrosion and malfunction of equipment). This test is applicable to all mechanical, hydro-mechanical, electrical, electronic, electrochemical, and electromechanical devices for which exposure to the effects of a dry dust (fine sand) laden atmosphere is anticipated.

3. Mechanical

a. Vibration. The vibration test is conducted to determine if the equipment is constructed to withstand expected dynamic vibrational stresses, and the performance degradations or malfunctions will not be produced by the simulated service vibration environment.

b. Acceleration. The acceleration test is intended to determine structural soundness and satisfactory performance of equipment in an environment of steady-state acceleration other than gravity.

c. Shock. The shock test is conducted to determine that structural integrity and performance of equipment are satisfactory with respect to the mechanical shock environment expected in handling, transportation, and service use.

System Compatibility Tests

Specific details of system interface requirements pertaining to hydraulic servocylinders should be delineated in the helicopter and systems detail specifications. In order to ensure that the hydraulic servocylinders are compatible with systems such as the hydraulic and flight control systems, the following should be included as a minimum:

1. Hydraulic system pressures versus requirements are met.

2. Hydraulic system surge pressure versus burst pressure margin of safety exists.

3. Servocylinder size is not too large for installation area.

4. Input linkage kinematics are mechanically adaptable to servocylinders, and cannot lock in place.

5. Output forces do not exceed design loads.

6. Flight control system is functional throughout the operational envelope.

Qualification Tests

Qualification testing of new or modified hydraulic servocylinders must be conducted prior to the first flight of the item being certified for U.S. Army operational flight use. The general requirements should be governed by MIL-T-5522C. The specific qualification test requirements to which the hydraulic servocylinder must be subjected should be delineated in the applicable contract specification. The types of tests should be as follows:

1. Visual

    a. Conforms to dimensional requirements

    b. No obvious defects

2. Proof pressure

    a. Pressure test to the required burst pressure

    b. Adequate margin of safety between system pressure and burst pressure

3. Leakage. Establish allowable leakage rate for length and frequency of stroke

4. Operational. Operate the hydraulic servocylinder in accordance with the operational environmental requirements to demonstrate the satisfactory operations, stroke, adjustment and leakage characteristics. For example, the hydraulic servocylinder requirements as a minimum might be:

   a. 30,000,000 cycles

   b. 3,000 psi system pressure

   c. 11 cps, stroke frequency

   d. 2.5-inch stroke length

   e. No gland seal replacement

   f. No adjustments allowed

   g. Endurance. Operate for 1,500 hours without a failure at a 95-percent confidence level

   h. Environmental conditions per contract specification

      - Vibration
      - Temperature
      - Sand and dust
      - Moisture

   i. Leakage rate of 1 drop in 200 cycles is allowable

These tests will uncover potential failure patterns such as leakage and binding.

Flight Testing

Flight testing of hydraulic system and components is required by MIL-T-5522C and MIL-H-5440F. Each airframe manufacturer, by the provisions of these specifications, must prepare and submit to the procuring agency a detailed test procedure including all flight tests. MIL-H-5440F requires these test procedures to be approved by the procuring agency, while MIL-T-5522C, the general military specification for testing of hydraulic system, only allows the procuring agency to comment on the test planned.

Both of these military specifications should require an approval by the procuring agency prior to the commencement of the flight test.

These specifications, while they cannot impose specific test provision, should enumerate certain categories of test that must be performed. Examples of these flight test provisions are provided by MIL-F-9490C for U.S. Air Force aircraft and MIL-F-18372 (Aer) for U.S. Navy aircraft. These 2 military specifications are referred to in MIL-H-5440F in the design requirements section for use by the Navy and Air Force; no requirement is discussed for U.S. Army aircraft.

Flight test plans for Army helicopters, whether developmental, preproduction or production test flights by airframe manufacturer personnel for a new or modified helicopter, should include sufficient parameters to demonstrate that the helicopter will perform to the projected operational requirements.

Maintenance test flight provisions by U.S. Army personnel are governed by TB AVN 23-16. These provisions are general in nature, and the detailed test flight criteria for each helicopter design are governed by the applicable Army technical manual for that helicopter. Army test flights should have maintenance verifications personnel in attendance to ensure proper adherence to flight test procedures and detection of all symptomatic hydraulic servocylinder failures, especially those due to excessive wear.

Service Testing

Service testing of helicopters and such essential equipment being supplied to the Army should be performed in general accordance with MIL-STD-471, Maintainability Demonstration Testing. Six test methods are specified in MIL-STD-471; the specific test method selected in maintainability demonstration must consider:

1. Risk. The probability that the task can be accomplished in a given time.

2. Cost. Allowable cost to conduct the demonstration.

3. Time. The time frame in which the test must be completed.

The method selection should be based upon these criteria and should include the particular hardware and procuring activity requirements.

The U.S. Army personnel assigned should possess hydraulic MOS (68) for the servocylinder tasks. Additionally, these personnel and those with a crew chief MOS (67) should be able to maintain the flight control system with hydraulic servocylinder installed. The service test plan provision should enumerate the types of failures that are projected to occur during the normal service of the helicopter within the projected operational parameters. Additional preventive maintenance checklist tasks should be included in the service test plans. The assigned personnel, 67 and 68 MOS, should be able to successfully demonstrate that each maintenance task can be accomplished by using the provided maintenance manuals, procedures, special tools, and spares provisioning.

Acceptance Testing

Acceptance testing requirements should be delineated in the test plan that each airframe manufacturer is required to submit to the procuring agency. This test plan should govern the scope and quantitative requirements of the acceptance test. In the case of the helicopter, the acceptance test must include provisions for both ground and flight tests. For procurement of such equipments as hydraulic servocylinders, these tests should include both operational tests in simulated operational environments and also a system compatibility test after installation in the designated helicopter.

SOLUTIONS

Immediate Design Improvements

"T" Seals With Rounded Corners

Recent tests using a "T" seal concept (see Figure 13) in UH-1H servocylinders have verified the failure modes and effects analysis conducted early in this program. Also, this type of "T" seal has been used in commercial fixed-wing applications with a significant improvement in MTBF (reduction of failures attributed to gland seals).

The "T" seal presents numerous advantages which are not provided by the inherent design concept of the "O" ring seal or the "O" ring with a TFE cap sleeve.

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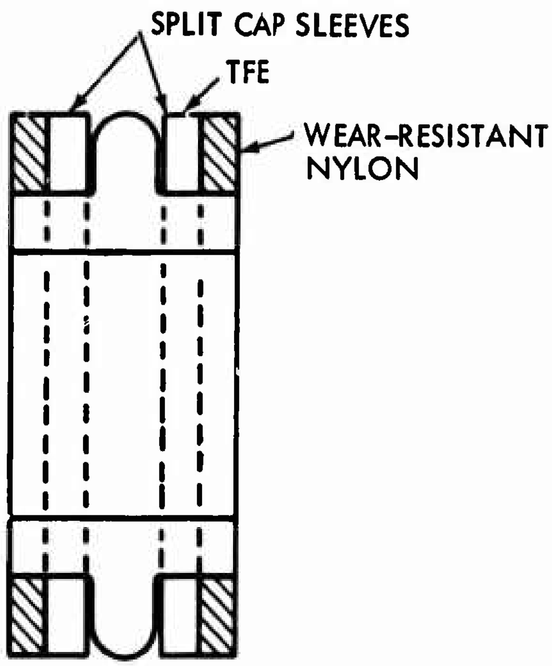


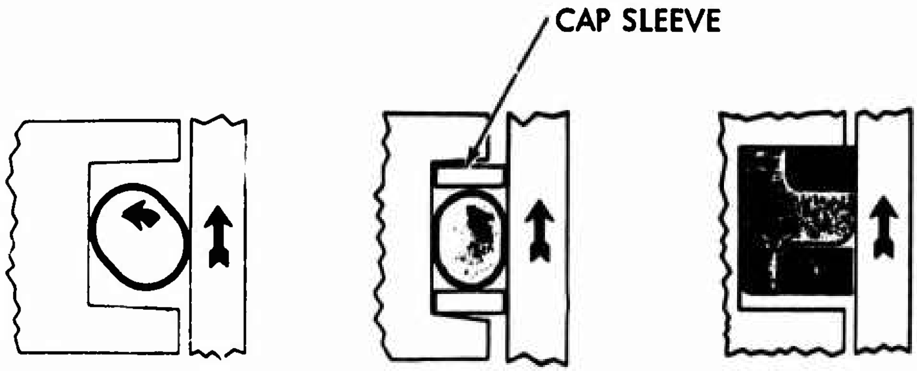
Figure 13. "T" Seal Cross-Sectional View.

The advantages of the "T" seal over the "O" ring with or without a TFE cap sleeve are as follows:

1. The "T" seal design minimizes spiraling tendencies inherent in the "O" ring design. Figure 14, detail (a) displays the operating tendency of an "O" ring with cap sleeves; and (c) displays the "T" seal and how spiraling is prevented by its design.

2. The "T" seal has only radial expansion, versus the axial and radial expansion of the "O" ring. Figure 15 displays this expansion.

3. Extrusion is minimized by the "T" seal design concept. Figure 16 displays the extrusion problems with "O" rings without TFE cap sleeves in detail (a), how it is minimized by the use of cap sleeves in detail (b), and how it is minimized by use of "T" seal in detail (c).

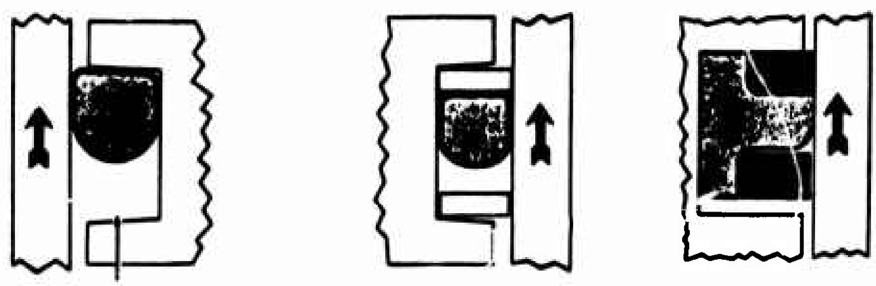


a. "O" RING SEAL WITHOUT CAP SLEEVES

b. "O" RING SEAL WITH CAP SLEEVES

c. "T" SEAL

Figure 14. Spiraling Problem Comparison of "T" Seal Versus "O" Ring Seal.



a. "O" RING SEAL WITHOUT CAP SLEEVES

b. "O" RING SEAL WITH CAP SLEEVES

c. "T" SEAL

Figure 15. Radial Versus Axial Expansion Comparison of "T" Seal Versus "O" Ring Seal.

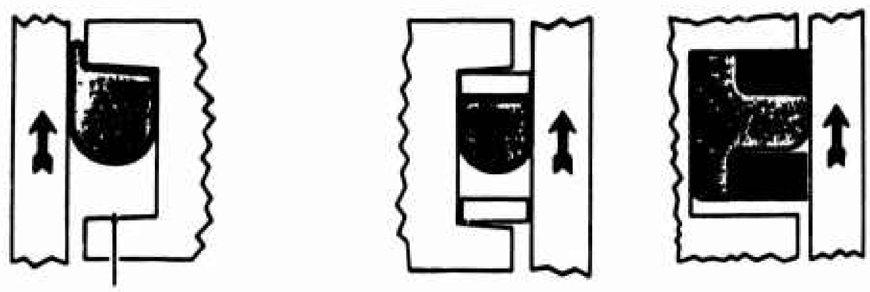


Figure 16. Extrusion Problem Comparison of "T" Seal Versus "O" Ring Seal.

4. Installation damage is substantially reduced by the inherent design of the "T" seal with its split backup rings. As shown in Figure 17, the cap sleeves for the "O" rings must rest completely in the groove, detail (a), while the split backup ring for the "T" seal only has to rest on part of the seal itself, detail (b). Detail (c) displays the ease of installing the split backup ring.

5. Leakage rate is reduced by more effective sealing surface.

6. Lower life-cycle cost (see Cost Comparison and Savings discussion).

7. MTBF was projected to a minimum of 750 hours, based on current U.S. Army tests of an actuator with "T" seals installed. The actuators were removed for reasons other than failure of the actuator. Teardown of the actuator revealed little wear after over 450 hours of operation. The same seals were left installed and the actuators were returned to the field for further test.

8. Direct interchange with current "O" ring with or without cap sleeves. Figure 18 displays the use of "T" seals versus six different "O" rings with and without cap sleeve installed. The six categories of "O" ring installations are as follows:

   a. Female (rod) regular groove type (FR)

   b. Male (piston) regular groove type (MR)

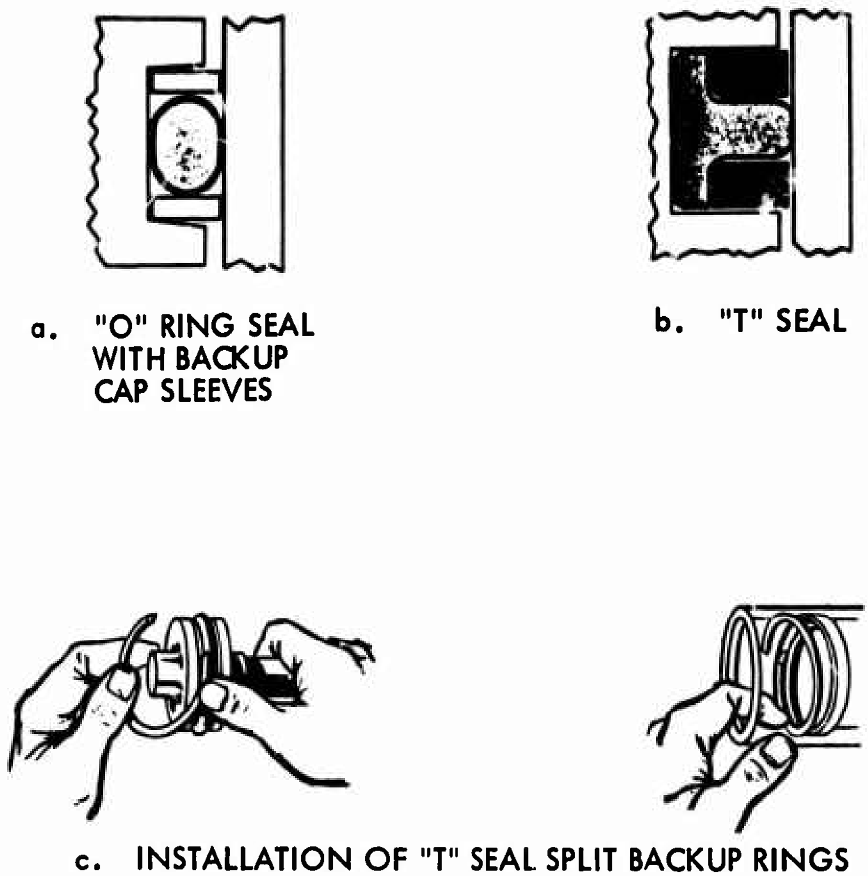


Figure 17. Installation Requirements of "O" Ring Cap Sleeve Versus "T" Seal Backup Ring.

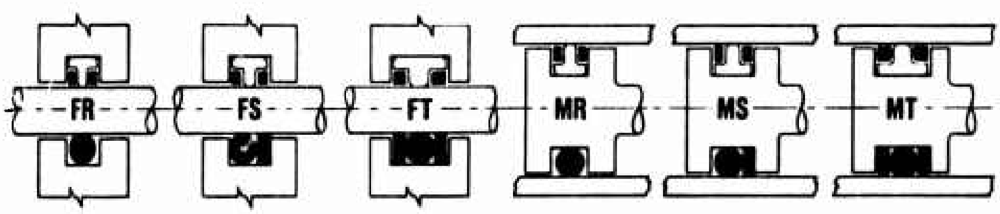


Figure 18. "T" Seal Replacement for "O" Ring Installation.

c. Female (rod) single backup groove type (FS)

d. Male (piston) single backup groove type (MS)

e. Female (rod) two backup groove type (FT)

f. Male (piston) two backup groove type (MT)

The disadvantages are as follows:

a. Increased procurement costs

b. Slight increase in system friction

c. Engineering and documentation cost associated with retrofit

In conclusion, further tests should be conducted in other classes of helicopter actuators in actual Army operating environments. The total life-cycle cost and helicopter availability should be considered when determining the feasibility of a complete retrofit of existing hydraulic servocylinder "O" ring sliding seals with the "T" sliding seal.

Less-Abrasive TFE Cap Sleeve

The abrasive nature of the various filled TFE cap sleeves and the associated wear caused to the sealing surface should be investigated. The result of this analysis was inconclusive as to the expected improvement to be realized by the use of a less-abrasive TFE impregnation. Test results of the TFE cap sleeve wear characteristics revealed that the most predominant impregnation, glass, is more abrasive than many other types of impregnated TFE cap sleeve.[1] The glass impregnation was used to increase the wear capabilities of the TFE cap sleeve. TFE without some impregnation would not result in a seal that would wear; consequently, glass impregnation of TFE was found to be desirable with respect to the wear of the cap sleeve.[2] However, the glass impregnated TFE cap sleeve was found to be very abrasive to such metals as aluminum.

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[1]Krauss, Hans G., LONG LIFE DYNAMIC SEALS, The Boeing Company, Vertol Division, Philadelphia, Pennsylvania; Presented at Combined Meeting No. 71 of SAE Committee A-6, Aerospace Fluid Power and Control Technologies, Seattle, Washington, October 4-8, 1971.

[2]Traub, H.A., UPDATING ACTUATOR PISTON RING SEALS OF "TEFLON" TFE, The Journal of Teflon, August 1965.

Improved Piston Rod Scrapers

Tests using Vietnam coral dust to study its effects on hydraulic servocylinders reveal a great disparity in the effectivity of the various piston rod scrapers.[3] Each scraper met or exceeded the requirements of MIL-S-5049B. Yet, each scraper did allow the ingestion of some of the coral dust.

To minimize or eliminate the wear of the gland seals in hydraulic servocylinders, a new improved type of piston rod scraper must be developed. The improved scraper should minimize the effects of external contamination from the gland seals.

Future Design Improvement

Recent development in gland seals has pushed the state of the art to a new and radical change. This development has provided the avenue to an improved servocylinder design that incorporates a nonsliding seal instead of the present "O" ring arrangement.

The nonsliding seal is a special rolling diaphragm seal which is used in lieu of sliding seals. Unlike ordinary rolling diaphragm seals which are generally suitable for lower pressure (< 3000 psi), the nonsliding seal's special construction can meet 5000 psi requirements.

The nonsliding seal construction uses an elastomeric-coated specially woven fabric preform made up of minute filaments configured to allow equal length in the rolling convolute. This construction assures that bending stresses in the convolute section all carry essentially the same load, thereby avoiding "telephone book tearing" types of failures. The elastomeric coating, held in compression, prevents fluid leakage through the weave. Very small shear stresses occur in the elastomeric coating due to pressure extrusion forces through the interstices in the woven fabric preform. This fabric preform is so tight that light will not penetrate.

The operation of the nonsliding seal is shown in Figure 19. Recalling that the seal is a conical shape folded back over itself, Figure 19 depicts a half cross section of the seal. The seal is shown in a neutral position at the top of the figure, while its stroking characteristics are shown below. Figure 19 also shows the relationship that the available stroke is four times its

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[3] Lefer, Henry, SCRAPER RING OVERCOMES VIETNAM DUST, Hydraulics and Pneumatics, August 1968.

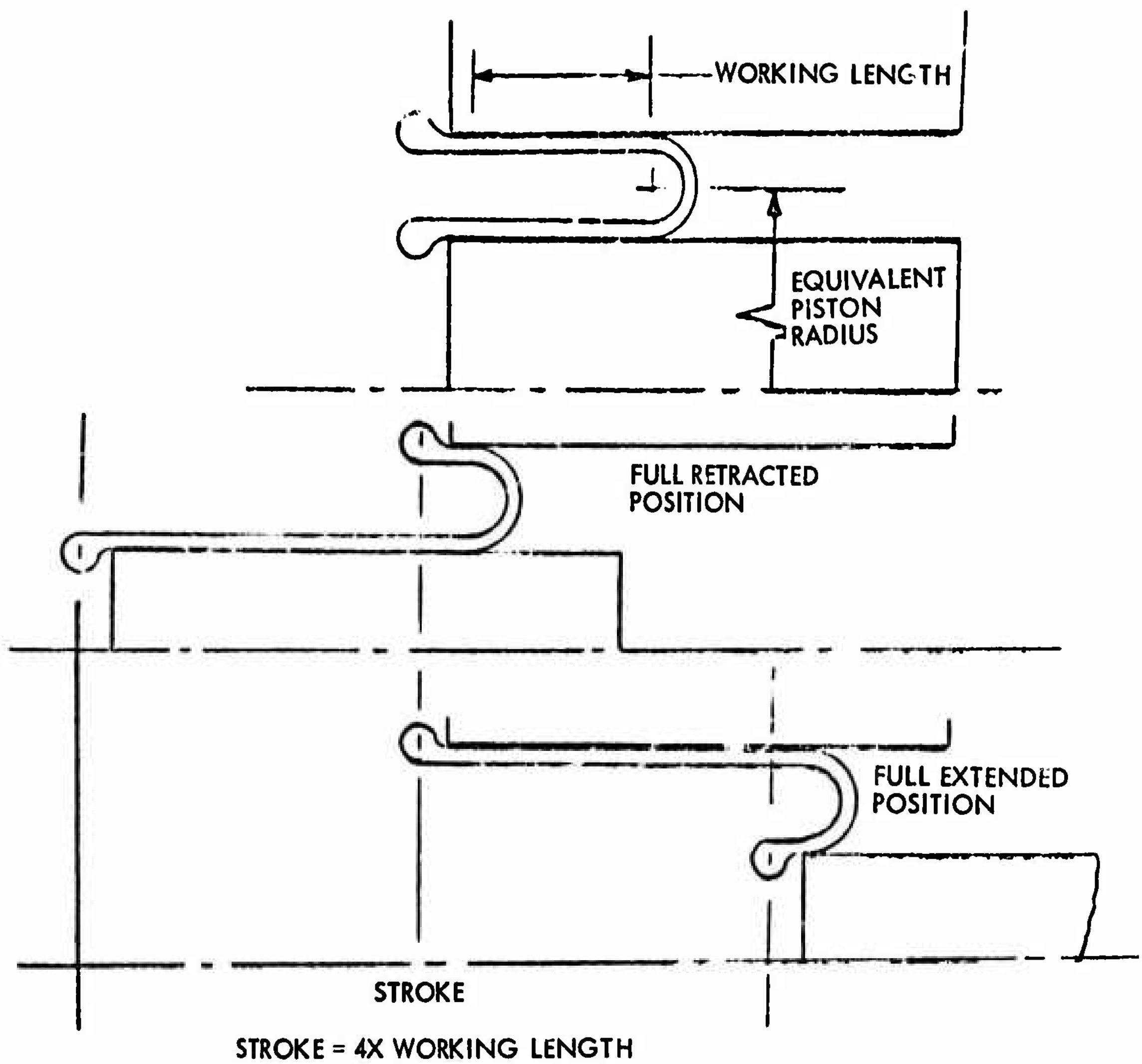


Figure 19. Operational Nonsliding Seal Characteristics.

working length. The stresses developed in the circular or convolute section are shown in Figure 20. Reasonable clearances between the piston and cylinder bore can result in relatively low fabric loads even at relatively high pressures.

Figure 21 schematically depicts a nonsliding seal actuator.

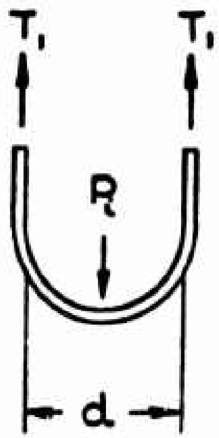
Most of the inherent (induced) failures caused by the "O" ring would be eliminated by this new concept. Sliding gland seals such as the "O" ring are a relatively low life component. This low life is further reduced when dust and dirt are introduced by the operational environment in areas such as those in which the U.S. Army helicopters must operate.

The nonsliding seal servocylinder, on the other hand, has the following projected advantages:

1. Negligible leakage.
2. Low hysteresis (negligible friction).
3. No wear problems.
    a. Inherent in the design concept.
    b. Contamination induced.
4. Lower life-cycle cost.
5. Close machining tolerances not required.
6. No special maintenance requirements.
7. Increased MTBF, approximately 757 hours.

The disadvantages are as follows:

1. Estimated development cost of $100,000; this does not include actual field test.
2. High individual unit acquisition cost (procurement cost) approximately $2675.
3. Cannot be retrofitted into existing servocylinders.
4. No proven failure history.
5. Current design concepts limit the size of nonsliding seal servocylinders.



NONSLIDING SEAL FORCES

- THE PISTON FACE SUPPORTS MOST OF THE PRESSURE LOAD
- THE NONSLIDING SEAL IS SUPPORTED IN ALL AREAS EXCEPT THE CONVOLUTE
- THE SMALL CONVOLUTE DIAMETER (d) RESULTS IN SMALL TENSILE LOADS "T" ON THE TECHROLL SEAL

$$T_1 = \frac{P_i d}{2}$$

Figure 20. Nonsliding Seal Stress Characteristics.

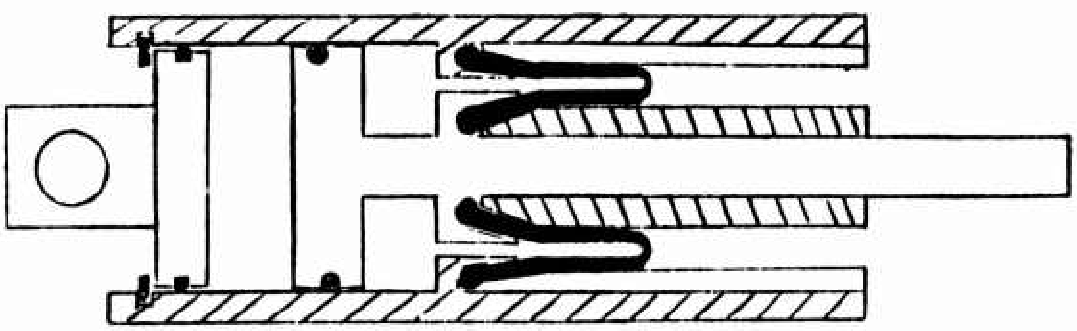


Figure 21. Hybrid Double-Acting Nonsliding Actuator.

The MTBF of 757 hours is based on a developmental unit and its accumulative cycles to failure; stroke length and system pressure were interpolated into the simulation parameters for the UH-1 servocylinder.

The projected cost savings by the use of the new seal concept were developed using the cost model developed for the servocylinder study. The unit cost and MTBF are stated above; the annual expense to maintain the UH-1H using the new servocylinder is shown in Table VII.

TABLE VII. ANNUAL NONSLIDING SEAL COST COMPARISON CHART

Confidence Level	Annual Cost	Projected Annual Savings
0.95	$21,404,412	$6,764,046
0.90	19,376,626	6,173,834
0.85	17,448,977	6,145,762
0.80	16,022,000	5,679,970

In conclusion, further investigations should be performed to determine the feasibility of using the nonsliding seal hydraulic servocylinder and its associated life-cycle cost and availability impacts on U.S. Army helicopter operations.

COST COMPARISONS AND SAVINGS

TOTAL COST SAVINGS

This section presents an estimation of the potential dollar savings that could be realized by the U.S. Army if improved hydraulic servocylinder designs were installed aboard their fleet of UH-1H helicopters. The definitions listed below are provided to facilitate comprehension of the remainder of this section.

Repair Cost	- the time required to remove and replace the malfunctioned part multiplied by the labor rate of the personnel performing the repair action
Checkout Cost	- the time required to check out and verify that the repair has been satisfactorily performed multiplied by the labor rate of the personnel performing the checkout action
Part Cost	- the dollar value of a replacement part
Maintenance Cost (total cost)	- the sum of the repair cost, the checkout cost, and the part cost
Current Costs	- maintenance costs associated with the current design hydraulic servocylinder
Expected Costs	- maintenance costs that would be associated with an improved hydraulic servocylinder design
Savings	- the current cost minus the expected cost

All maintenance costs and savings shown in this section are presented at various confidence levels and/or risk levels. Confidence level as used in this section is in complete conformance with the definition presented in Chapter 20 of U.S. Army Technical Manual TM 38-715-1 entitled "Provisioning Techniques". This manual defines confidence level as "... a statistical determination of the probability of the repair parts' being available if one is demanded." The risk level presents the probability that parts will not be available when demanded. Risk levels are obtained by subtracting confidence levels from unity (the value of one). Potential cost savings represent the dollar value of the maintenance costs that would not have to be expended upon a new design. These savings result from a reduction in the number of maintenance actions required and the number of parts required to support a fleet of 1833 UH-1H helicopters for 1 year.

Specifically excluded from this analysis are logistics system costs, training costs, maintenance facilities costs, maintenance tooling costs, and savings that would be realized from increased helicopter availability. The determination of these costs and potential savings in these areas of cost is beyond the scope of this investigation.

A summary of the results of the cost savings analysis is presented in Table VIII. This table presents the current maintenance cost, maintenance costs that would be incurred for the three improved designs, and the savings that would be realized for each of the three improved designs. The greatest savings can be obtained at the highest confidence level (i.e., lowest risk level) for each particular design. This situation exists because more parts must be stocked to compensate for the reduced risk of not having parts to perform a repair when such a repair must be performed. Any improvements in the mean time between failures (MTBF) of the servocylinder result in a more rapid reduction in the requirement for replacement parts and maintenance actions at the higher confidence levels than at the lower confidence levels. This greater difference between the expected number of failures of the present servocylinder design and the expected number of failures for the improved servocylinder design accounts for a greater cost savings at the higher confidence SL levels.

The failure data necessary to compute the current cost figures were extracted from the U.S. Army MISS report data on the UH-1H servocylinders. These data cover the period from 1 January 1964 to 30 January 1970.

These MISS data show that the current design's MTBF is 335 hours. This corresponds to a failure rate (λ or 1/MTBF) of 0.00298 failures per hour. The average flight time per helicopter per month was given in MISS as 73.8 hours. The computations presented herein are based on that information as it applied to a group of 10 aircraft maintained by a team of 5 maintenance men. The repair and checkout cost was calculated on 3.8 hours per maintenance action at a repair rate of \$16.50 per hour. The total unscheduled maintenance cost (C_t) of \$1723.70 was computed by adding the repair and checkout cost (\$62.70) to the cost of the part (\$1661).

The next parameter required is the annual operating time for the servocylinder population. The annual operating time is determined by multiplying the helicopter group's monthly flight time x 12 months x 3 servocylinders per aircraft. The annual operating time was determined to be 26,568 hours. The expected failures (U) is found according to the formula $U = \lambda t = 79.1$. When the U value has been computed, the Poisson tables are used to find the number of spares required for maintaining certain levels of confidence. Table VIII lists 4 different levels of confidence ranging from 0.80 to 0.95. From this table the Army can evaluate various cost versus risk ratios prior to making a provision and maintenance level decision. Table IX lists the numbers of spares required for each confidence level, for each group of 10 UH-1H's flying for 1 year.

TABLE VIII. MAINTENANCE COST COMPARISONS AND SAVINGS ASSOCIATED WITH PRESENT DESIGN AND IMPROVED DESIGNS FOR 1833 UH-1H HELICOPTERS (DOLLARS)

	Present Design		Improved Designs					
	335-Hour MTBF		500-Hour MTBF		1000-Hour MTBF		1500-Hour MTBF	
Confi-dence Levels	Maint. Cost	Cost Savings	Maint. Cost	Cost Savings	Maint. Cost	Cost Savings	Maint. Cost	Cost Savings
0.95	28,168,458	0	20,201,370	7,967,086	11,188,437	16,980,021	7,769,814	20,398,644
0.90	25,550,460	0	18,254,982	7,295,478	10,010,832	15,539,628	7,066,362	18,484,098
0.85	23,594,739	0	16,962,680	6,632,059	8,898,375	14,696,364	6,117,690	17,477,049
0.80	21,701,970	0	15,441,357	6,260,613	8,113,305	13,588,665	5,495,039	16,205,931

TABLE IX. ANNUAL NUMBER OF SPARES REQUIRED FOR PRESENT 335-HOUR MTBF DESIGN SERVOCYLINDERS FOR 10 UH-1H'S	
Confidence Level	Number of Spares
0.95	94
0.90	90
0.85	88
0.80	86

Using the cost model state equation for the expected costs, values are found based on the groups of 10 helicopters per year. These cost values are shown in Table X.

The expected annual spares cost values shown in Table X were multiplied by 183 to give the values on the cost comparison table. At the time of the MISS (1 Jan 1964 to 30 June 1970) the total UH-1H helicopter population was 1833. The resulting values shown on the tables in this section represent the total population of UH-1H's, unless otherwise specified.

The expected costs for the improved servocylinder were computed using the method described in the appendix as well as the same time and repair cost factors. The part cost was assumed to be slightly higher ($1725) and the MTBF was set at 500 hours. This 500-hour MTBF resulted from tests conducted at the U.S. Army Test Board at Cairnes AAF. These tests were terminated after 477 hours due to a failure in another part of the helicopter. No servocylinder failure was detected during the 477 hours, and it is felt that the unit probably would last much longer than the 477 hours. Therefore, the cost projections based on an MTBF of 500 hours should be considered as the minimum savings possible. If the unit had a real MTBF closer to 700 or 800 hours, the resultant savings would be substantially increased. With an MTBF of 500 hours the failure rate becomes 0.002. These figures yield the estimated costs associated with the improved design and are shown in Table XI.

The costs shown in Table X must be multiplied by 183 to arrive at the total projected cost figures for Table VIII and Table XII. Additionally, the number of spares required to maintain each confidence level are reduced.

The decrease in servocylinder failure incidents results in increased helicopter availability. As a result of this increased availability, the total quantity of helicopters required to be on hand to perform any given mission is reduced.

TABLE X. ANNUAL COST OF SPARES FOR 10 UH-1H'S

Confidence Level	Expected Costs on Group of 10
0.95	$153,926
0.90	139,620
0.85	128,933
0.80	118,590

TABLE XI. ANNUAL COSTS OF 500-HOUR MTBF SERVOCYLINDERS FOR 10 UH-1H'S

Confidence Level	Number of Spares	Expected Costs on Group of 10
0.95	65	$110,390
0.90	62	99,754
0.85	61	92,692
0.80	59	84,379

Tables X and XI indicate the minimum amount of maintenance cost savings possible from introduction of the improved servocylinders aboard UH-1H helicopters. Recent tests at Ft. Rucker indicate that the servocylinder MTBF could reach 1500 hours. As a result of this test data, cost savings projections were performed upon the UH-1H servocylinder with an MTBF of 1000 hours and again at 1500 hours. The results of these projections are listed in Tables XII and XIII.

The results of this total cost savings analysis are presented in Figures 22 and 23. Figure 22 represents the annual maintenance cost savings that can be realized using a 500-hour MTBF servocylinder as compared

TABLE XII. COST OF COMPARISON OF PRESENT SERVO-CYLINDER WITH 1000-HOUR MTBF SERVO-CYLINDER FOR UH-1H

Confidence Level	Current Cost	Projected Cost	Potential Savings
0.95	$28,168,458	$11,188,437	$16,980,021
0.90	25,550,460	10,010,832	15,539,628
0.85	23,594,739	8,898,375	14,696,364
0.80	21,701,970	8,113,305	13,588,665

TABLE XIII. COST OF COMPARISON OF PRESENT 335-HOUR MTBF DESIGN SERVOCYLINDER WITH 1500-HOUR MTBF CYLINDER

Confidence Level	Current Cost	Projected Cost	Potential Annual Savings
0.95	$28,168,458	$7,769,814	$20,398,644
0.90	25,550,460	7,066,362	18,484,098
0.85	23,594,739	6,117,690	17,477,049
0.80	21,701,970	5,496,039	16,205,931

to the present 335-hour design. Figure 23 depicts the projected cost savings, at various confidence levels, that would be realized if the UH-1H actuator MTBF were increased from the present 335-hour MTBF design to 1000-hour MTBF and 1500-hour MTBF.

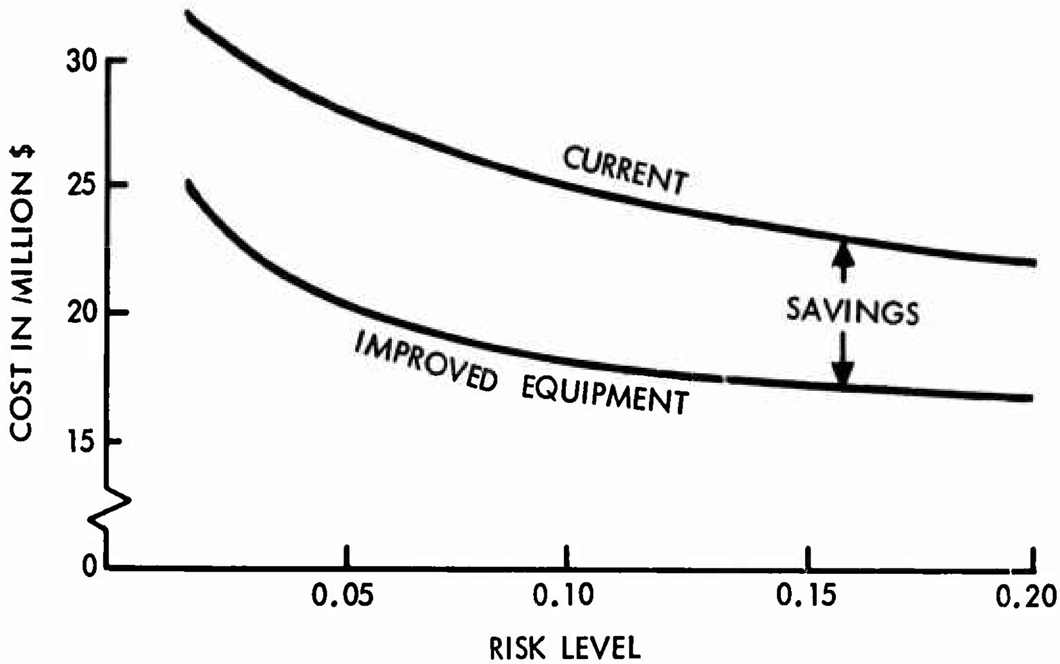


Figure 22. Annual Maintenance Cost Versus Various Risk Levels for 500-Hour UH-1H Servocylinder.

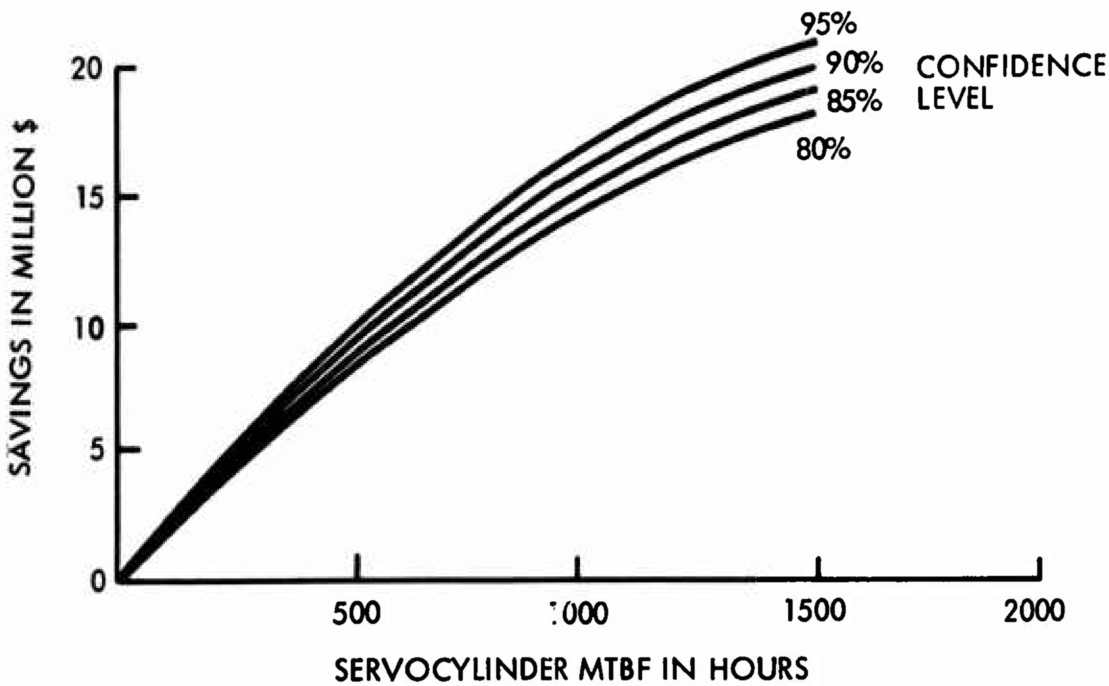


Figure 23. UH-1H Projected Savings as Related to Confidence Levels.

The results of this total UH-1H helicopter servocylinder cost savings analysis are graphically presented in Figures 22 and 23. Figure 22 indicates the annual maintenance cost savings that can be realized from using a 500-hour MTBF servocylinder in place of the present 335-hour MTBF design. These savings are shown at risk levels ranging from 0.05 to 0.20.

Figure 23 shows that the rate of cost savings decreases beyond 1000 hours MTBF. These savings tend to "level out" at about 1000 hours MTBF. Therefore, it would not be judicious from a purely cost savings standpoint to expend money to improve the present design beyond the 1500-hour MTBF shown. The 1500-hour MTBF appears to be the limit of the present hydraulic seal state of the art. Any increase beyond this point would probably require a new generation of servocylinders.

COST SAVINGS RELATED TO FAILURE MODES

The following 5 failure modes account for 91 percent of all recorded UH-1H servocylinder removals during the period ranging from 1 January 1964 to 30 June 1970:

1. Leaking: 46%

2. No failure: 31%

3. Unknown reason: 6%

4. Internal failure: 2%

5. Excessive wear: 4%

The maintenance cost savings that can be realized from the elimination of these various failure modes are presented in Table XIV. These savings are the expected maintenance cost savings that would be realized by elimination of the various failure modes and would result in a 500-hour MTBF design. The savings shown in Table XIV are obtained by multiplying the total savings shown for a specific design (see Table VIII) by the percentage of total failures attributable to each failure mode as shown above. As an example, the $3,664,860 savings shown in Table XIV for elimination of leaking, at 0.95 confidence level was obtained by multiplying 7,967,086 (total savings at 0.05 confidence level from Table VIII) by 0.46.

The use of a 500-hour MTBF servocylinder as the basis for the savings shown in Table XIV represents a conservative estimate. It is felt that this estimate is conservative because it is based upon minimum design improvements. Indications are that attainable performance in excess of the 500 hour MTBF is well within the present state-of-the-art capabilities of servocylinders. Therefore, it is reasonable to assume that

TABLE XIV. UH-1H EXPECTED ANNUAL SAVINGS RESULTING FROM ELIMINATION OF VARIOUS FAILURE MODES RESULTING IN A 500-HOUR MTBF DESIGN

	Confidence Level			
Failure Mode	0.95	0.90	0.85	0.80
Leaking	$3,664,860	$3,355,920	$3,050,747	$2,879,882
No Failure	2,629,138	2,407,508	2,188,579	2,066,002
Unknown	478,025	437,729	397,924	375,637
Internal Failure	159,342	145,909	132,641	125,212
Excessive Wear	318,684	291,818	265,282	250,424

the actual savings realized from the elimination of the depicted failure modes from the fleet of UH-1H's should be greater than those shown in Table XIV.

COST SAVINGS RESULTING FROM IMPROVED DESIGNS, POLICIES, PRACTICES, AND PROCEDURES

This section presents the potential savings in maintenance costs that can be realized by elimination of inadequacies in various policies, practices and procedures. The following paragraphs present the rationale used to determine the contribution of the various policies, practices and procedures to the existence of the five predominant failure modes presented in the previous section.

1. Leaking

The leaking of hydraulic servocylinders is caused by the seal technology used in each particular servocylinder. Discussions conducted with various vendor personnel during this investigation indicate that the vendor QA as presently practiced meets or exceeds the present formal requirements. There is sufficient evidence that the environmental testing and the qualification testing presently being performed by the vendors does not adequately identify inherent design weakness. These various procedures represent about 30 percent of the contribution to the leaking problem, while the remaining 70 percent is attributed to design approaches and practices.

2. No Failure and Unknown

   This particular category presents strong evidence that the maintenance personnel are erroneously removing servocylinders from aircraft. It is reasonably safe to assume that maintenance personnel would not remove nonfailed articles from the helicopters if they were properly trained. The removal of servocylinders for unknown reasons also indicates the "trial and error" guesswork situation that exists with maintenance personnel. Therefore, 100 percent of the costs associated with the no-failure and unknown removal situation are considered to be caused by improper training and lack of quality assurance and personnel familiarization with documentations such as TM's, maintenance cards, etc.

3. Internal Failures and Excessive Wear

   These 2 categories are considered as normal wear of the servocylinders in the helicopter operational environment. The data analyzed during this investigation do not indicate any contribution of the previously discussed factors to the internal failure and excessive wear modes. Little or no improvement in these categories will be realized by changing the design, policies and/or governing procedures. It is possible that design changes would reduce, but not eliminate, these situations; therefore, 20 percent of the cost savings associated with these modes is attributed to design.

The potential savings resulting from improvements in design, environmental and qualification testing, and maintenance policies, practices and procedures are shown in Table XV for 500-hour MTBF design servocylinders used aboard 1833 UH-1H helicopters.

TABLE XV. ANNUAL COST SAVINGS RESULTING FROM CORRECTING VARIOUS FAILURE CAUSES FOR UH-1H

Cause	Anticipated Savings
Design Deficiencies	$2,436,690
Quality Assurance and Testing Procedures	1,006,776
Maintenance Policies and Training	2,845,237

CONCLUSIONS

The most salient point indicated by the data analyzed and by discussions held with airframe manufacturer, vendor and U.S. Army personnel in support of this report is that the various policies, practices, and procedures contribute to the premature failure of hydraulic servocylinders. The predominant failure modes and percent of total UH-1 servocylinder removals during the period ranging from 1 January 1964 to 30 June 1970 are as follows:

1. Leaking: 46%
2. No failure: 31%
3. Unknown reason: 6%
4. Internal failure: 2%
5. Excessive wear: 4%

The following listing delineates these failure modes and the degree that they are affected by the inadequacies of the various policies, practices and procedures:

1. Leaking

   The leaking of hydraulic servocylinders is caused by the seal technology used in each particular servocylinder. Discussions with various personnel conducted during this investigation indicate that the vendor QA as presently practiced meets or exceeds the present formal requirements. On the other hand, it is evident that the environmental testing and the qualification testing presently being performed do not adequately identify inherent design weakness. These various procedures represent about 30 percent of the contribution to the leaking problem, while the remaining 70 percent is attributed to design approaches and practices.

2. No Failure and Unknown

   This particular category presents strong evidence that the maintenance personnel are erroneously removing servocylinders from aircraft. It is reasonably safe to presume that these personnel would not remove not-failed articles from the helicopters if they were properly trained. The removal of servocylinders for unknown reasons also indicates the "trial and error" guesswork situation that exists with maintenance personnel. Therefore, 100 percent of the costs associated with the no-failure and unknown removal situation are considered caused by improper training, lack of quality assurance, and documentation such as TM's, maintenance cards, etc.

3. Internal Failures and Excessive Wear

These 2 categories are considered as normal wear of the servocylinders in the helicopter operational environment. The data analyzed during this investigation do not indicate any significant contribution of the QA and testing policies and/or governing procedures to the internal failure and excessive wear failure modes. Little or no improvement in these categories will be realized by changing the design, policies and/or governing procedures. It is possible that design changes would reduce but not eliminate these situations, so 20 percent of the cost savings associated with these modes is attributed to design.

RECOMMENDATIONS

The recommended solutions and revisions to remedy the inherent failure modes of the servocylinder are presented in summary form in this section and are discussed in detail in the Revisions and Solutions section. The specific recommendations are as follows:

1. Incorporate U.S. Army environmental and operational requirements into all applicable specifications and documents.

2. Apply realistic maintainability, reliability, safety, human factors and quality assurance parameters to each procurement of Army hardware.

3. Revise and upgrade maintenance requirements and procedures.

4. Investigate the use of nonsliding or rolling seals in lieu of sliding seals; this will reduce the inherent wear and resultant leakage characteristics of sliding seals.

5. Perform additional in-service testing of hydraulic servocylinders with "T" seals installed. If in-service tests continue to display increased wear characteristics, use "T" seals with rounded corners in lieu of "O" rings and "O" rings with TFE cap sleeves. The inherent wear characteristics of the seals and barrel surfaces are minimized by the application of this concept.

6. A lesser improvement can be achieved by the use of less abrasive TFE cap sleeves for "O" rings. The present TFE cap sleeves contain an abrasive glass-filled TFE which causes excessive wear of the actuator barrel surface. A rouge or graphite impregnated TFE cap sleeve has been shown to reduce this rapid wear of barrel surfaces.

7. Conduct additional testing in the area of piston rod end scrapers to exclude environment induced dust and dirt, such as coral dust, from being ingested into the servocylinder.

8. Provide contracts to the airframe manufacturers to analyze current in-house raw data. This analysis should provide the Army with a better data base for assessing failure modes, failure causes and operational environments in which these failures occurred.

9. Hydraulic system filtration requirements and devices should be of such a nature that when the filters reach their capacity, maintenance personnel cannot reset the filter indicator without replacing the filter element.

ABBREVIATIONS AND ACRONYMS

AIMD	Aircraft Intermediate Maintenance Department (USN)
AQL	Acceptable Quality Level
ARADMAC	U.S. Army Aeronautical Depot Maintenance Center, Corpus Christi, Texas
AVSCOM	U.S. Army Aviation Systems Command, St. Louis, Missouri
DS	Direct Support
FAA	Federal Aviation Administration
FARADA	Failure Rate Data (FARADA) Program
FMSAEG	Fleet Missile Systems Analysis and Evaluation Group
GS	General Support
LOR	Level of Repair
MIL SPEC	Military Specification (sometimes only MIL)
MIL-STD or MS	Military Standard
MISS	Major Item Special Study
MMH/FH	Maintenance Man-Hours per Flight Hour
M or D	Malfunction or Defect
MOS	Military Occupational Specialty
67 MOS	Helicopter Crew Chief MOS
68 MOS	Helicopter Hydraulic Technician MOS
MTBF	Mean-Time-Between-Failures
MTTR	Mean-Time-To-Repair
NAVAIR	Naval Air Systems Command

OJT	On-the-Job Training
OPNAV	Office of the Chief of Naval Operations
PMD	Preventive Maintenance Daily
PMI	Preventive Maintenance Intermediate
PMP	Preventive Maintenance Periodic
QA	Quality Assurance
QC	Quality Control
RAMMIT	Reliability and Maintainability Management Improvement Techniques
SOW	Statement of Work
TAMMS	The Army Maintenance Management System
TB	Technical Bulletin
TBO	Time Between Overhauls
TM	Technical Manual
TSLI	Flight Hours Since Last Installation
TSLO	Flight Hours Since Last Overhaul
TSN	Flight Hours Since New
USAAAVS	U.S. Army Agency for Aviation Safety

GLOSSARY

Accessibility	A measure of the relative ease of admission to the various areas of an item.
Availability	A measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown (random) point in time.
Calendar Maintenance	Scheduled preventive maintenance performed at intervals measured in terms of days.
Capability	A measure of the ability of an item to achieve mission objectives, given the conditions during the mission.
Demonstrated	That which has been proven by the use of concrete evidence gathered under specified conditions.
Failure	The inability of an item to perform within previously specified limits.
Failure Analysis	The logical, systematic examination of an item or its diagram(s) to identify and analyze the probability, causes, and consequences of potential and real failures.
Failure Cause	The probable cause of the failure mode.
Failure Mode	The potential mode of failure associated with equipment function.
Failure Rate	The number of failures of an item per unit measure of life (cycles, time, miles, events, etc., as applicable for the item).
Human Engineering	The area of human factors which applies scientific knowledge to the design of items to achieve effective man-machine integration and utilization.

Human Factors	A body of scientific facts about human characteristics. The term covers all biomedical and psychosocial considerations; it includes, but is not limited to, principles and applications in the areas of human engineering, personnel selection, training, life support, job performance aids, and human performance evaluation.
Inherent	Achievable under ideal conditions, generally derived by analysis, and potentially present in the design.
Intermediate Maintenance (USN)	Equivalent in depth to DS/GS levels and performed at calendar intervals.
Life Cycle	The total existence of an item starting with the initiation of the basic concept and continuing through design, development, production, operational use, and eventual disposal.
Life-Cycle Cost	The total cost that is attributed to the item throughout its life cycle.
Maintainability	A characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources.
Maintenance	All actions necessary for retaining an item in or restoring it to a specified condition.
Maintenance Man-Hours per Flight Hour	The number of maintenance hours expended per flight hour to keep the helicopter flying.
Maintenance, Preventive	The actions performed in an attempt to retain an item in a specified condition by providing systematic inspection, detection, and prevention of incipient failure.
Maintenance, Unscheduled	The actions performed, as a result of failure, to restore an item to a specified condition.

Maintenance Verification	Quality assurance/control inspections subsequent to maintenance actions at U.S. Army facilities.
Mean-Time-Between-Failures (MTBF)	For a particular interval, the total functioning life of a population of an item divided by the total number of failures within the population during the measurement interval. The definition holds for time, cycles, miles, events, or other measure of life units.
Mean-Time-To-Repair (MTTR)	The total corrective maintenance time divided by the total number of corrective maintenance actions during a given period of time.
Operational Readiness	The capability of a helicopter or component to perform its intended function when called upon to do so.
Quality Assurance	Quality control inspections subsequent to maintenance or manufacture at vendor or manufacturers' facilities.
Reliability	The probability that an item will perform its intended function for a specified interval under stated conditions.
Safety	The conservation of human life and its effectiveness, and the prevention of damage to items, consistent with mission requirements.
Storage Life (Shelf Life)	The length of time an item can be stored under specified conditions and still meet specified requirements.
Wearout	The process of attrition which results in an increase of the failure rate with increasing age (cycles, time, miles, events, etc., as applicable for the item).

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APPENDIX
COST MODEL

This cost model has been created to assist the Army in its decision to implement new equipment or procedures. It can be used to estimate costs for continuing operations and for new systems.

The objective is to estimate the number of spares required to keep a group of equipment operating over a certain period of time. In order to do this, there must be some way to project the number of chance failures that will occur within that period. Past performance has already indicated that point at which normal equipment "wearouts" will occur, and steps have been taken to replace parts before this expected wearout time. This is the effective preventive maintenance situation. Therefore, it is only the chance failures, the unexpected ones, that cause repair costs that are out of the normally expected projections. It is not possible to predict exactly when chance failures will occur, but over a long period of time their frequency is approximately constant. This constant rate was formulated by Poisson and a table constructed that lists the expected number of failures (U) and the probability of when those failures will occur.

The Poisson tables are set up to indicate three different probabilities: P(x), that exactly x number of failures will occur; C(x), that x or fewer failures will occur; and D(x), that x or more failures will occur in a given time. Since the task considered here is predicting the number of spares required for a certain length of time, it is the C(x) probabilities that prove most helpful. If the probability is very high that x or fewer failures will occur in a given time, then the probability of more than x failures is very low. By storing enough spares for x number of failures, there is little possibility of running out of spares during the time period considered.

In addition to projecting the number of failures, it is necessary to convert these numbers into dollar values. This is accomplished by determining the time required to repair (T_r) and check out (T_{co}) a malfunction and multiplying that time by the military labor rate (R_r) for such work. In using this model, it is assumed that the labor rate is the same for checkout and maintenance personnel.

$$\text{Repair Cost} = C_r = T_r R_r$$

$$\text{Checkout Cost} = C_{co} = T_{co} R_r$$

Next, the total unscheduled maintenance cost (C_t) for each repair action is determined by adding the part cost (C_p) to the repair and checkout costs. This part cost includes logistics and administrative costs.

$$C_t = C_p + C_r + C_{co}$$

or

$$C_t = C_p + R_r(T_r + T_{co})$$

At this point it becomes necessary to further examine the predictive portion of the cost model. The model is based on the well-known exponential formula for reliability $R(x) = e^{-\lambda t}$. In the formula, e is the natural log base 2.71828, λ is the chance failure rate, and t is the operating time for which we are seeking the reliability of a population of equipments. This formula was expanded by Poisson into one that gives the probability (P) that a certain number of failures (X) will occur in the same period of time (t). The formula reads

$$P_{(X)} = \frac{(\lambda t)^X e^{-\lambda t}}{X!} = P_{nx} \text{ of the cost model}$$

This formula has been proven valid, and the tables of the Poisson distribution have been used extensively by reliability engineers and probability statisticians.

When the expected number of failures (U or λt) is known, the tables can be used directly to find the probability of those failures occurring. If the tables indicate that the probability of that number of failures (x) occurring is very high, then it can be assumed with some confidence that (x) number of spares will be sufficient to keep the population operative. If a higher degree of confidence is required, the tables are set up to indicate the extra number of spares that should be stored.

As an example, assume that an item of equipment is to be exposed to operation for a period of 200 hours with a failure rate of 0.1 and a corresponding MTBF of 10 hours. We would then expect 20 failures to occur.

$$U = \lambda t = 0.1 \times 200 = 20$$

The probability that exactly 20 failures will occur is $P(x) = 0.08883532$. Thus, exactly 20 failures are expected to occur less than once in 10 samples. The probability that 20 or fewer failures will be observed is $C(2) = 0.55909258$. The probability that 20 or more failures will be observed is D(20) = 0.52974374. If spares are to be provided to assure 90-percent confidence that the 200 hours of operation can be completed, 26 spares would be required, i.e., C(26) = 0.92211322.

In order to use this formula, certain data are required. It is necessary to search the maintenance data to determine the actual failure rate (λ) for the certain item under consideration. These data will also indicate the number of items (n) on each piece of equipment. Aviation records indicate the average number of flight hours per piece of equipment in a group. In this particular case, the total operating time (T) for a group of helicopters must be determined. This time is further expanded to indicate the operating time of all study items that are operative on each helicopter in the group. This total operating time per item is multiplied by the number of items in the group to produce the time (t) used in the formula.

The cost model combines the probability of failure (P_{nx}) with the cost of unscheduled maintenance (C_t) associated with that number of repairs (Z) to indicate the expected cost for unscheduled maintenance.

$$Ce = ZC_t P_{nx}$$

or

$$Ce = ZC_t \sum_{i=1}^{x} \frac{(\lambda t)^i}{i!} e^{-\ t}$$